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Bis-TEGylated Poly(*p*-benzamide)s: Combining Organosolubility with Shape Persistence

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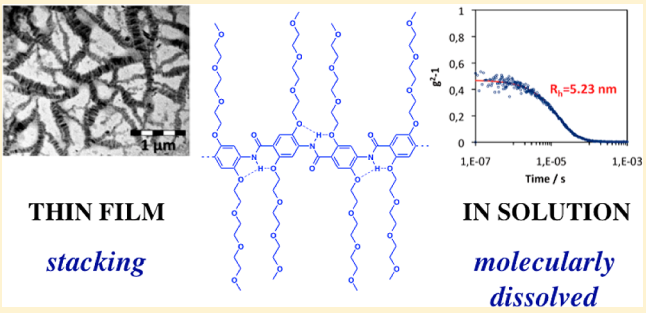
Supporting Information

ABSTRACT: The synthesis of perfectly planar, bis-substituted aromatic polyamides is reported herein. With highly flexible triethylene glycol chains attached and conformational restriction through intramolecular, bifurcated hydrogen bonds these are among the most shape-persistent yet organo-soluble polymers to date. Starting from 4-nitrosalicylic acid, our group developed a route to phenyl-2,5-bis-TEGylated aminobenzoate, which could be polymerized by addition of lithium bis(trimethylsilyl)amide (LiHMDS). Since this technique has not been applied to step-growth polycondensations of polyaramides so far, the influence of two different solvents and an N-protective group was investigated. Therefore, substituted phenyl aminobenzoate derivatives carrying a free amine or an N-protective group have been polymerized. Additionally, the tendency for self-assembly of the readily soluble bis-TEGylated poly(*p*-benzamide) was observed by transmission electron microscopy (TEM) in the dried state. Dynamic light scattering (DLS) measurements of chloroform solutions did not indicate the formation of aggregates. Thus, intermolecular interactions, which other aromatic polyamides typically exhibit, are prevented. The access to bis-substituted, entirely rigid poly(*p*-benzamide)s via this new polycondensation method paves the way for exciting new structures in materials science and supramolecular chemistry.



INTRODUCTION

Aromatic polyamides have been the subject of intensive studies with regard to synthesis and characterization for decades. From the first report in the early 1960s by Kwolek et al.[1] until nowadays, they play an important role in industry owing to their exceptional chemical and mechanical properties, among them high fiber strength and resistance to chemicals and temperature.[2] With their rigid aromatic backbone combined with the double-bond character of the amide bond and their strong hydrogen-bonding pattern, they also represent interesting nanoscopic objects for self-assembly and supramolecular chemistry. Even though this makes their fabrication and processing challenging, they remain highly interesting materials due to their shape persistence. Efforts have been made to overcome the synthetic limitations with different approaches to higher solubility in organic solvents.[3] One approach is to synthesize block copolymers with a solubility mediating flexible block,[4] and the other is the introduction of N-protecting groups. Unprotected aromatic polyamides possess a *trans*-conformation of their amide bonds, whereas tertiary aromatic amides exhibit a *cis*-conformation[5] suppressing hydrogen bond formation and resulting in a coil-like structure of the polymer chain.[6] A third one is the attachment of flexible side chains,[7] a method which has been studied in our group to solubilize poly(*p*-benzamide)s.[8] As described manifold by groups working on substituted aromatic oligoamides, alkyloxy side chains not only ease the synthesis but also account for intramolecular hydrogen bond formation, rendering the oligomer backbone perfectly planar.[9] Given the fact that these structures exhibit high rigidity and shape persistence, their increased organosolubility makes them promising candidates for high-performance materials. Herein we report the synthesis of completely flat, rigid-rod-like bis-TEGylated poly(*p*-benzamide)s, which molecularly dissolve in organic solvents. To the best of our knowledge this is the first report on alkyloxy-bis-substituted poly(*p*-benzamide)s so far, joining the class of already described bis-substituted aromatic hydrazide polymers[10] and poly(1,4-phenylene terephthalamide)s.[11]

The most commonly described polymerization techniques for aromatic polyamides rely on a step-growth mechanism, which ideally leads to a polydispersity index of 2. In the original process the polycondensation is mediated by the reaction of amines with acid chlorides derived from the corresponding carboxylic acids *in situ* (depending on AB or AA/BB systems from the amino acid or diacid, respectively).[12] Moreover, polymerization techniques employing milder reagents have been developed over the past decades. Higashi and Yamazaki et al.[13] as well as Ogata et al.[14] examined the activation of the

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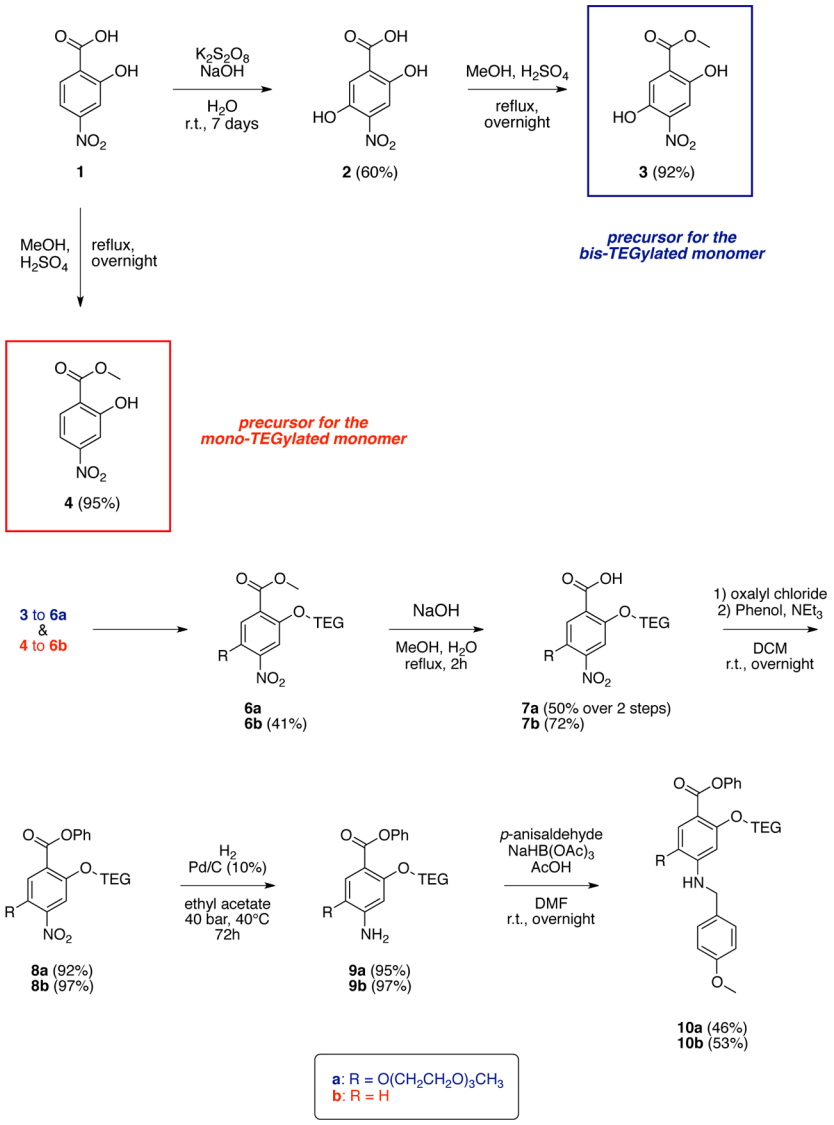
Scheme 1. Synthesis to Bis-TEGylated (a) and Mono-TEGylated (b) Monomer



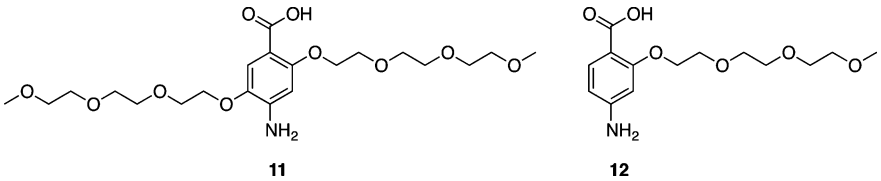
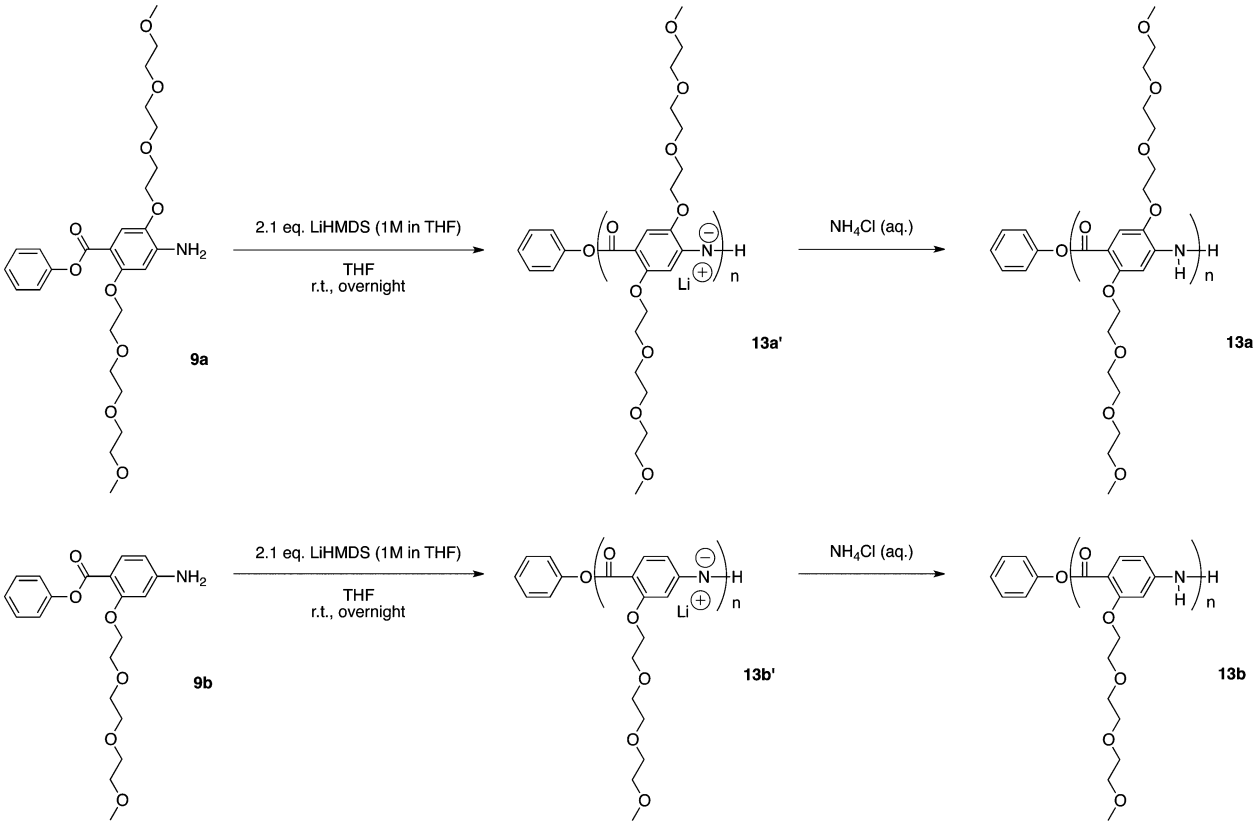


Figure 1. Bis-TEGylated amino acid **11** and mono-TEGylated amino acid **12** as monomers for polycondensation.

carboxylic acid moiety via active esters using phosphorus-derived compounds (triphenylphosphite and triphenylphosphine, respectively). Since prior manipulation of the amino acid or diacid is not necessary, this is a simple and straightforward approach to aromatic polyamides. However, the activation of the carboxylic acid via phosphorylation appears to be insufficient regarding the bis-TEGylated aromatic amino acids investigated by us. The group of Yokozawa et al. reported a remarkable technique in which N-alkylated or N-protected phenyl aminobenzoate monomers are reacted with an initiator in the presence of a strong and sterically demanding base.[15] In this way Yokozawa et al. gained access to well-defined, high molecular weight polymers with a narrow molecular weight distribution with a PDI of 1.1.[6c,16] This method differs from the ones described above since it proceeds via a chain-growth polycondensation mechanism. The +*M* effect of the aminyl anion deactivates the N-protected monomer and suppresses self-polycondensation, so that the monomers react selectively with the initiator or the propagating chain end.[16c,17] It is also stated that phenyl aminobenzoate could not be polymerized under the same polycondensation conditions that were applied to the protected monomers. We employed a variation of this technique to TEGylated monomers showing that self-polycondensation of bis-TEGylated phenyl aminobenzoate without the use of initiator proceeds well to high molecular weights. The synthesis and characterization of monomers, the

Scheme 2. Polycondensation of TEG-Substituted Phenyl Aminobenzoates Using LiHMDS



modified polymerization protocol, and the results are reported herein.

■ RESULTS AND DISCUSSION

Monomer Synthesis. The monomer synthesis involved two routes starting both from 4-nitrosalicylic acid (**1**) leading to mono- and bis-TEGylated monomers as outlined in Scheme 1.

The mono-TEGylated monomer **12** (Figure 1) served as a model as it had previously been polymerized in our research group following Yamazaki conditions.[8] The monomer synthesis was altered following the procedure employed for the bis-TEGylated monomer, which will be described in the following. The first step was the hydroxylation via Elbs persulfate oxidation[18] of 4-nitrosalicylic acid (**1**) which succeeded in 60% yield. This crucial step allowed for the introduction of a second functionality in the 5-position of the monomer and subsequently in the polyaramide backbone. Protection of the carboxylic acid as a methyl ester yielded the precursors **3** and **4** in up to 95% yield, followed by TEGylation with triethylene glycol bromide **5**.

Owing to two attached triethylene glycol chains in product **6a**, the separation from excess triethylene glycol bromide via column chromatography was difficult, leading to a high loss of product. Instead, the methyl ester was hydrolyzed in alkaline solution, yielding the carboxylate and offering the possibility to remove excess triethylene glycol monomethyl ether by extraction with dichloromethane. Subsequent acidification of the aqueous phase and extraction with dichloromethane afforded product **7a** in 50% yield over two steps. Mono-TEGylated product **6b** could be synthesized and purified by column chromatography in 41% yield and hydrolyzed afterward to the carboxylic acid **7b** (72%). The phenyl ester was introduced via an acid chloride by *in situ* activation of the carboxylic acid with oxalyl chloride. Subsequent reaction with phenol under basic conditions generated **8a** (92%) and **8b** (97%). Hydrogenation of the nitro group with palladium on activated charcoal at 40 bar of H_2 and 40 °C over 3 days resulted in monomers **9a** and **9b** in high yields (≥95%), which were either purified by recycling HPLC (**9a**) or column chromatography (**9b**) to obtain high-purity products for polycondensation. The N-protected monomers **10a** and **10b** were obtained by introduction of the PMB protecting group via reductive amination with *p*-anisaldehyde and sodium triacetoxy borohydride under acidic conditions. Both monomers were purified by recycling HPLC to obtain **10a** (46%) and **10b** (53%). The overall yield for the bis-TEGylated monomer (**a**) was 11%; the synthesis of mono-TEGylated monomer (**b**) succeeded in 14% overall yield.

Polymerizations. *First Investigations.* Our initial investigations aimed for the polycondensation of bis-TEGylated amino acid **11** (Figure 1) in order to develop a synthetic strategy and investigate the aggregation behavior of bis-substituted poly(*p*-benzamide)s. In analogy to our previous report on the polymerization of amino acid **12**,[8] we also polymerized amino acid **11** via Yamazaki conditions with triphenyl phosphite and pyridine in NMP at 100 °C.[13b] GPC analysis revealed low molecular weights with M_n of around 3000 g/mol, indicating the formation of oligomers. Varying the procedure using 2 equiv of freshly distilled triphenyl phosphite or microwave irradiation (150 °C, 30 min, 2 equiv of triphenyl phosphite) did not give higher molecular weight polymers. Another polycondensation technique following the protocol of Ogata et al.[14a] using triphenylphosphine and hexachloroethane in pyridine at room temperature as well as at 100 °C yielded in

slightly higher molecular weights (M_n in the range of 4000 g/mol), as revealed by GPC analysis in chloroform. These first investigations on the polycondensation of bis-TEGylated monomer **11** hint at the low reactivity of the amino group caused by an electron-rich aromatic system and the steric hindrance due to the second triethylene glycol chain.

Polycondensation of Phenyl Aminobenzoate Derivatives. A polymerization technique which is not based on the formation of activated esters—which is the basic principle in Yamazaki and Ogata-type polycondensations[13a,14b]—but on the formation of highly reactive aminyl anions by addition of a strong base is described by Yokozawa et al., the first report on chain-growth polycondensation of aromatic amino acids.[15a,b] In his group Ohishi et al. described the polymerization of N-protected phenyl-3-amino benzoates which possess an alkyloxy side group in the 4-position,[19] and Yoshino et al. investigated the polymerization of *N*-TEGylated phenyl-4-amino benzoates.[20] Both monomers could be polymerized by chain growth condensation polymerization despite the low reactivity of the amino group. For the polymerization of our monomers without the use of initiator, we hypothesized that lithium bis(trimethylsilyl)amide (LiHMDS) would deprotonate the amino group of the phenyl aminobenzoate derivative, which could then undergo self-condensation as shown in Scheme 2. An essential difference to the Yokozawa-type polycondensation is the usage of at least 2 equiv of base. 1 equiv is necessary to abstract a proton from the reacting amino group, the second one to deprotonate the amide of the growing polymer chain. Caution was also taken toward minimizing moisture during the reaction since the aminyl anion is very sensitive to water. Therefore, each monomer was dried at 40 °C on a Schlenk line overnight, purged with argon, and transferred into a glovebox to carry out the polycondensation.

Monomer **9b** served as control since mono-TEGylated poly(*p*-benzamide) had already been investigated in our group (see amino acid **12** in Figure 1). In fact, during the polymerization with 2.1 equiv of LiHMDS (1 M in THF) in THF ([monomer] = 0.5 mol/L) the solution rapidly turned viscous after 5−10 min, and a precipitate appeared during stirring at room temperature overnight. The polymerization was quenched, and the precipitate was dispersed twice in methanol and centrifuged to remove cleaved phenol. Polymer **13b** appeared to be insoluble in THF, DCM, DMF, and DMSO, and only after 2 days of stirring in chloroform, a sample for gel permeation chromatography was partially dissolved, the rest forming an insoluble gel. Gel permeation chromatography of the soluble fraction revealed a very high molecular weight (M_n > 230 000 g/mol, PDI > 11), which could be explained by the formation of strong aggregates as described previously (Figure S1 in the Supporting Information).[8] We believe that amide bond formation occurred faster and led to higher molecular weight polymers in this Yokozawa-type polycondensation than the synthesis of mono-TEGylated poly(*p*-benzamide)s via Yamazaki conditions. The latter were soluble in organic solvents as chloroform, DMF, and DMSO.[8]

The same conditions were applied to monomer **9a**, forming bis-TEGylated poly(*p*-benzamide) **13a**. Similar to polymerization **13b**, the solution turned rapidly viscous and a solid precipitated during overnight stirring. Nonetheless, subsequent work-up provided polymers completely soluble in dichloromethane, chloroform, diglyme, acetone, DMF, and hot DMSO allowing for full characterization of the polymer. Gel permeation chromatography in chloroform indicated high molecular weights with M_n of 12 100 g/mol and M_w of 29 800 g/mol, giving a polydispersity of 2.5. As shown in Figure 2,

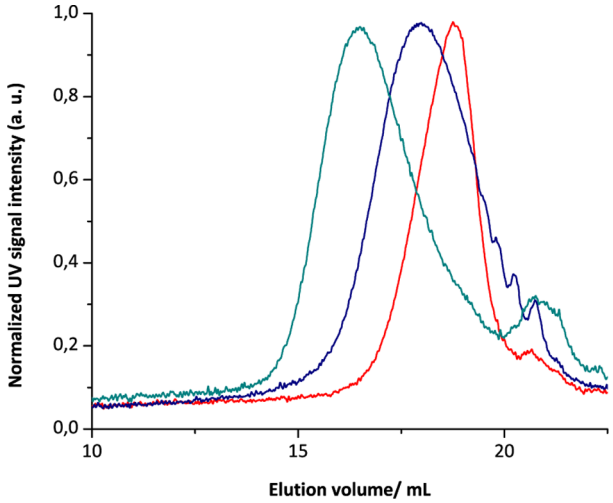


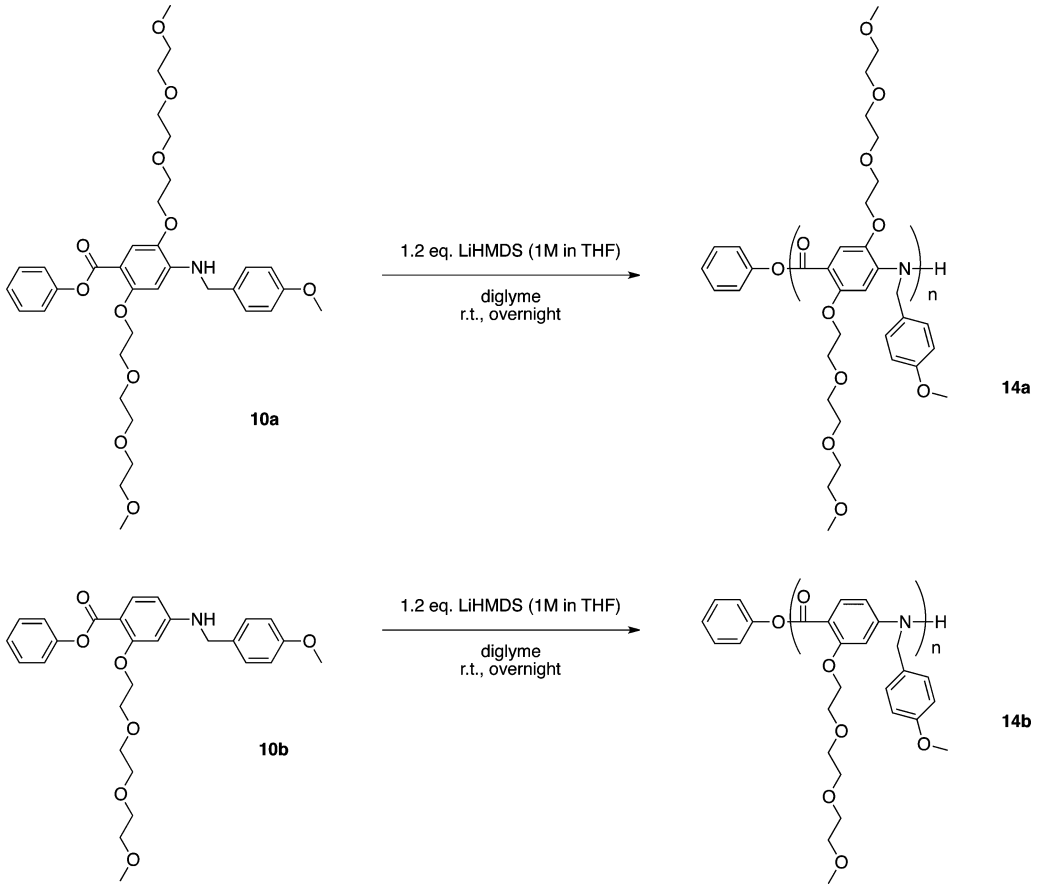
Figure 2. GPC traces of polymerizations of bis-TEGylated monomer carried out under Yamazaki (red), Ogata (blue), and Yokozawa-like (green) conditions.

the peak of polymer **13a** in the GPC elugram is shifted significantly to higher molecular weights under Yokozawa-like conditions compared to Yamazaki and Ogata conditions. End-group analysis via NMR spectroscopy supports the result obtained by GPC, showing a number of 25 repeat units (Figure S5). That corresponds to a molecular weight of 11 100 g/mol.

Both polymers bis-TEGylated poly(*p*-benzamide) (**13a**) and mono-TEGylated poly(*p*-benzamide) (**13b**) showed the same behavior during polymerization: After a few minutes the solution turned viscous. Unlike Yokozawa et al. who use N-protected monomers, the monomers **9a** and **9b** possess a free amino group resulting in polyanions **13a′** and **13b′** which might render the growing polymer chains during polymerization less soluble in THF (see Scheme 2). After protonation by quenching with saturated ammonium chloride solution, polymer **13a** became very well organo-soluble, whereas **13b** stayed partly insoluble, showing the solubility-mediating effect the second triethylene glycol side chain possesses.

Polycondensation of N-Protected Monomers. Based on the results described above, our second approach was consequently to transform the primary into a secondary amine, providing an N-protected monomer. We chose the acid labile *p*-methoxybenzyl protecting group (PMB), allowing for a straightforward recovery of the rigid polyaramide backbone as described previously.[6a,b] Introduction of the *N*-PMB group should render the polymer soluble during polycondensation by preventing the formation of a polyanion and further leading to a coil-like polymer which has also been described as a solubility-enhancing factor (Scheme 3).[6] Furthermore, the protecting group can be removed by treatment with trifluoroacetic acid, resulting in the perfectly planar bis-TEGylated poly(*p*-benzamide). As a matter of fact, the first study using **10b** as monomer did not result in precipitation during polymerization. According to GPC analysis the polymerization succeeded to very high molecular weights of polymer **14b** with M_n of 36 000 g/mol and M_w of 83 000 g/mol, giving a polydispersity of 2.3. MALDI-ToF mass spectrometry revealed the presence of high molecular weight polymers with either the phenyl or the phenyl

Scheme 3. Yokozawa-Type Polycondensation of N-Protected Monomers 10a and 10b



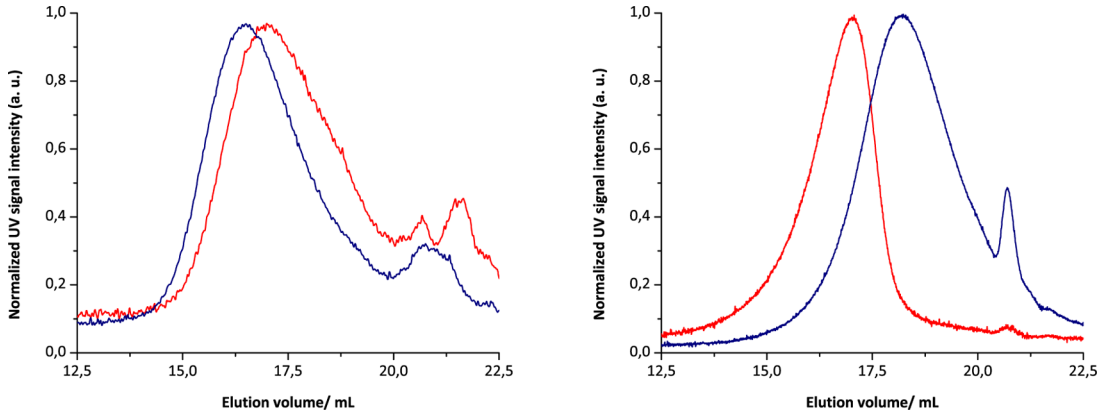


Figure 3. GPC elugrams of polycondensations in THF (blue) and diglyme (red). Left: bis-TEGylated poly(*p*-benzamide), **13a**; right: N-protected, mono-TEGylated poly(*p*-benzamide), **14b**.

and the PMB protective end group missing (Figure S11). The mass difference of the peaks in both distributions corresponded to the repeating unit. Unfortunately, we were not able to translate these very promising results onto the bis-TEGylated monomer **10a**. All attempts to polymerize **10a** at different temperatures (room temperature or 50 °C) or in different solvents (THF or diglyme) showed no formation of polymer by GPC analysis (Figure S2). In fact, aside from recovering monomer, rather short oligomers were formed, with M_n of 800 g/mol, M_w of 1300 g/mol, and a PDI of 1.6. We believe that the sterical hindrance caused by the bulky PMB protecting group and the second triethylene glycol chain in the 5-position diminishes the reactivity of the aminyl anion and thereby greatly decreases the reaction rate.

Effect of the Solvent. Two different solvents have been utilized in the polycondensation reactions described above: tetrahydrofuran and diglyme. As shown by the GPC elugrams in Figure 3, THF is the more suitable solvent in polycondensations of unprotected phenyl aminobenzoate derivatives (left), whereas the use of diglyme leads to higher molecular weight polymers in polycondensations of N-protected monomers (right).

We believe that this influence of the solvent depends on two factors: the solubilization of the polyanion and the reactivity of

the aminyl anion. As described for anionic polymerizations, polymerization rates depend on the nature of the solvent and the counterion. Solely the change from THF to 1,2-dimethoxyethane (DME) results in a 7-fold increase of the propagation rate constant during anionic polymerization of styrene.[21] Owing to the oligodentate coordination of the counterion and the creation of a "naked" anion,[22] linear oligoethers as DME and diglyme enhance the reactivity of the chain end. This is reflected in the superiority of diglyme over THF in polymerizations **14a** and **b** (Figure 3, right, and Figure S2). However, this effect is irrelevant regarding unprotected bis-TEGylated monomer **9a** where the solubilization of the polyanionic chain **13a′** seems to be the limiting factor. Following the same principle as above, a polyanion is more stable and better solubilized in a solvent where the counterion is not complexed, i.e., where the anions are bound in ion pairs. This is predominantly the case in THF as indicated in Figure 3, left.

Investigation of the Self-Assembly of Bis-TEGylated Poly(p-benzamide)s. In the Dried State. To investigate the polymers' aggregation behavior in the dried state, chloroform solutions (c = 0.1 and 0.5 mg/mL) were drop-cast onto carbon-coated copper grids and visualized by transmission electron microscopy (TEM) (Figure 4).

Because of the rigid and perfectly planar backbone caused by three-center hydrogen bonds between the amide bonds and alkyloxy side chains, bis-TEGylated poly(p-benzamide)s organize in large, micrometer-long supramolecular stacks. These columnar bundles comprise fibers with lengths (l) between 140 and 200 nm and widths (d) between 20 and 30 nm (Figure 4). This deviation in length and width observed on the different micrographs is probably due to the drying effects of the chloroform solutions where the solvent evaporates rapidly.

As described before,[8] the driving force for the formation of supramolecular structures is the interaction between aromatic units, in our case most likely through face-to-face orientation of the planar, rigidified aromatic backbone (Figure 5).

In Solution. During the characterization of polymer **13a** in solution we did not see any evidence for the formation of aggregates. GPC analysis showed a unimodal distribution with a small peak assigned to short oligomers and residual monomer. Therefore, the formation of aggregates could be excluded, assuming that the peak detected corresponds to the polymer (Figure S4). Also, a strong broadening of peaks in the ^{1}H NMR spectrum, which generally results from the formation of aggregates, could not be observed (Figure S6). A possible explanation for this phenomenon might be the strong solubilizing effect of the triethylene glycol chains acting as "bound solvent" on the substituted poly(p-benzamide),[11] which leads to stabilization of single chains in solution and prevents aggregation through aromatic interactions. Dynamic light scattering (DLS) measurements were conducted over a time window of 12 h and confirmed the molecularly dissolved state of polymer **13a**. The correlation function is shown in Figure 6 and was fitted with the cumulant method resulting in a hydrodynamic radius of 5.2 nm. This radius was calculated assuming that the polymer possesses the shape of a hard sphere. The relation between the hydrodynamic radius and the actual dimension of a nonspherical scatterer, such as the bis-TEGylated poly(p-benzamide), depends on its particular shape and cannot be assessed from DLS measurements alone. However, it serves as an estimation of the polymer's dimension

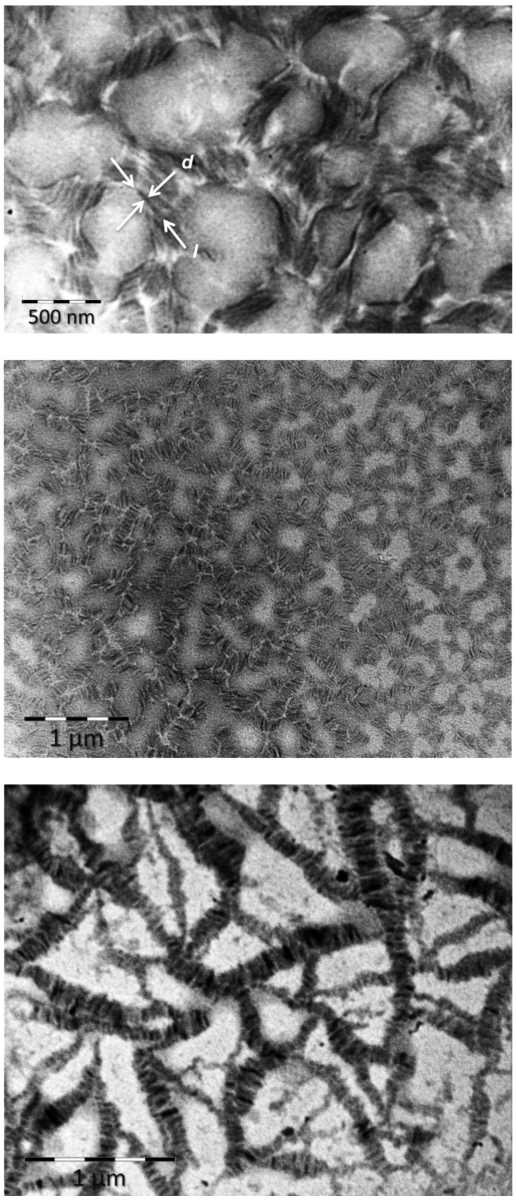


Figure 4. TEM micrographs of polymer **13a**, drop-cast from chloroform solution; top: c = 0.5 mg/mL, stained with iodine, length l = 198 ± 32 nm, diameter d = 25 ± 4 nm; middle: c = 0.5 mg/mL, stained with iodine, l = 137 ± 20 nm, d = 22 ± 4 nm, bottom: c = 0.1 mg/mL, stained with 4% aqueous OsO_4 solution, l = 140 ± 28 nm, d = 31 ± 6 nm.

and allows us to investigate its tendency to form aggregates in solution over time. Plotting the hydrodynamic radius as a function of time illustrates distinctly that the polymer chains do not self-assemble within the time window observed. Applying the method of CONTIN reveals a hydrodynamic radius of 6 nm, which is in good agreement with the cumulant results (see Figure S13).

To ensure that formed aggregates were not removed by filtration prior to the DLS measurements, a UV spectrum of the unfiltered and filtered solution (c = 10 mg/mL) was recorded at a concentration of c = 0.005 mg/mL. A blue-shift of the unfiltered solution, which is typical for the formation of H aggregates, could not be observed (Figure S12). As described in previous reports by our group, UV spectra in chloroform of unsubsituted oligo(p-benzamide)s (up to n = 4) show a red-

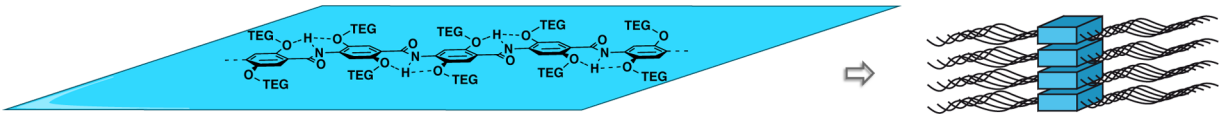


Figure 5. Proposed $\pi-\pi$ interactions of the perfectly planar bis-TEGylated poly(*p*-benzamide).

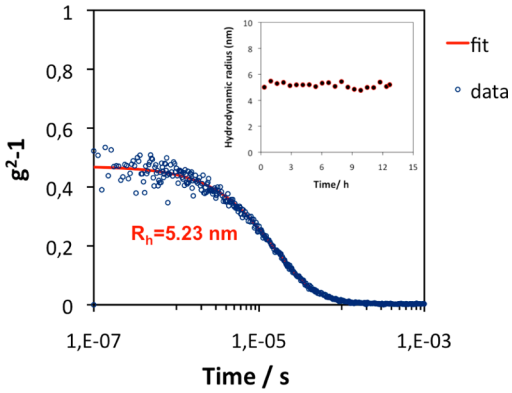


Figure 6. Correlation function corresponding to a hydrodynamic radius of 5.2 nm and the hydrodynamic radius as a function of time (inset).

shift with increasing aramide length due to the partial conjugation of the backbone.[23] At a critical oligomer length where the rigid rods start to self-assemble, the UV spectra display a blue-shift compared to shorter oligomers.[4e] This was also observed for mono-TEGylated poly(*p*-benzamide)s (λ_{max} = 340 nm) which exhibit a blue-shift of $\Delta\lambda_{max}$ = 10 nm compared to the mono-TEGylated hepta(*p*-benzamide).[8] The UV spectrum in chloroform of bis-TEGylated poly(*p*-benzamide) (**13a**) is shifted significantly to higher wavelenghts (λ_{max} = 387 nm). Because of the bifurcated hydrogen-bonding pattern, the phenyl rings are aligned perfectly coplanar, which enhances the conjugation of the polymer backbone. In addition, the two triethylene glycol chains donate electrons to the aromatic backbone. The high absorption maximum also indicates that a formation of H aggregates does not take place in chloroform solutions.

To sum up, the investigations on the self-assembly of bis-TEGylated poly(*p*-benzamide)s via TEM and DLS revealed two different behaviors: The polymer employs a self-assembling behavior in the dried state, which is driven by the completely flat polymer backbone facilitating aromatic, noncovalent interactions. However, the polymer chains remain molecularly dissolved in chloroform solutions due to the solubilization through the triethylene glycol side chains.

■ EXPERIMENTAL SECTION

Materials. Solvents of analytical grade were purchased from Honeywell, Acros Organics, Sigma-Aldrich, Fisher Scientific, and Fluka and were used without further purification. Solvents of technical grade were purified by distillation, if necessary. Tetrahydrofuran and diglyme for the use in polymerizations were purchased as sealed bottles from Acros Organics (extra dry, AcroSeal) and transferred into a glovebox. Acetone was dried over molecular sieves (3 Å). *N*-Methylpyrrolidone (extra dry) was purchased from Acros Organics. Triethylamine (Acros) was freshly distilled before usage. Deuterated solvents ($CDCl_3$, DMSO-d_6) were purchased from Cambridge Isotope Laboratories, Inc. DMSO-d_6 was stored over molecular sieves (3 Å). All further chemicals were purchased from Sigma-Aldrich, Acros Organics, Alfa Aesar, and Merck and used as received.

2,5-Dihydroxy-4-nitrobenzoic acid (**2**) and triethylene glycol bromide (**5**) were synthesized according to the literature.[24]

Techniques. Standard ^{1}H and ^{13}C nuclear magnetic resonance spectra were recorded on a Bruker Avance III 300 at a frequency of 300 and 75 MHz, respectively, at a Bruker DPX 360 at a frequency of 360 MHz (^{1}H) and 90 MHz (^{13}C) or at 400 MHz (^{1}H) and 100 MHz (^{13}C) on a Bruker DPX 400 spectrometer. All NMR signals were referenced internally to residual solvent signals. Matrix-assisted laser desorption and ionization (MALDI) mass spectra were recorded on a Bruker FTMS 4.7T BioAPEX II, and electron spray ionization (ESI) mass spectra were recorded on a Bruker-Ion Trap MS esquire HCT mass spectrometer. Matrix-assisted laser desorption and ionization time-of-flight (MALDI-ToF) measurements were performed on a Bruker ultrafleXtreme MALDI-ToF mass spectrometer. DCTB was used as matrix, and sodium trifluoroacetate was used as salt. RP-HPLC analysis was performed on a HP 1090 liquid chromatograph (Hewlett-Packard) using a PerfectSil column (MZ Analysentechnik, Mainz, Germany, 250 × 4.0 mm; 120 ODS-2.5 μm). Samples were dissolved in acetonitrile and eluted with an acetonitrile/water gradient buffered with 0.1% TFA starting from 10% acetonitrile rising to 100% over a period of 40 min. UV signals were detected at 254 nm. For recycling HPLC a Japan Analytical Industry Next System equipped with a preparative MZ Kromasil C18 Column and a UV detector at 254 nm was used. 10 wt % solutions of the sample in acetonitrile were prepared and eluted in acetonitrile/water (75/25). For gel permeation chromatography in chloroform an instrument consisting of a Duratec vacuum degasser, a JASCO PU-2087plus pump, and a set of two MZ-Gel SD_{plus} linear columns (300 × 8 mm, 5 μm particle size) was used. Signal detection occurred by use of an Applied Biosystems 759A UV detector (set to 254 nm wavelength) and a Knauer Smartline 2300 RI-Detektor (refractive index). Calibration was done using Malvern Polycal UCS-PS polystyrene standards. TEM measurements were done at a FEI/Philips CM-100 Biotwin transmission electron microscope operating at 80 kV equipped with a LaB_6 emitter and fitted with a MegaView III CCD camera. Images were acquired and processed with iTEM (Olympus) software; length and thickness of the fibers were measured with help of ImageJ. The hydrodynamic radius was assessed by dynamic light scattering (DLS) using a 3D LS spectrometer equipped with a polarizer situated in front of the detector (LS Instruments AG, Fribourg, Switzerland). Measurements were performed in cylindrical glass cells of 10 mm diameter at a scattering angle of 90°. We used two commonly applied approaches to fit correlation functions from DLS, namely the cumulant[25] and the CONTIN[26] method. Both methods reveal a mean diffusion coefficient along with its distribution which can be transferred into a hydrodynamic radius following the Stokes−Einstein relation.[27] Each measurement was done in chloroform for 160 s at 25 °C; a viscosity of 0.542 mPa·s and a refractive index of 1.45 were used to calculate hydrodynamic radii. The sample was dissolved in 2-fold filtered chloroform (0.2 μm PTFE filter), c = 10 mg/mL, and filtered through a 0.2 μm PTFE filter. UV−vis measurements were accomplished in chloroform at c = 0.05 mg/mL on a JASCO V-630 spectrophotometer.

Methyl 2,5-Dihydroxy-4-nitrobenzoate (3). 2,5-Dihydroxy-4-nitrobenzoic acid (**2**) (10.06 g, 0.051 mol) was dissolved in methanol (150 mL) and concentrated sulfuric acid (12 mL) and heated under reflux overnight. Brown needles were built upon cooling and filtered under vacuum to give **3** (10 g, 0.047 mol, 92%). ^{1}H NMR (300 MHz, DMSO-d_6): δ (ppm) = 3.87 (s, 3H, CH_3), 7.40 (s, 1H, Ar−H^6), 7.42 (s, 1H, Ar−H^3), 10.06 (br s, 1H, OH), 10.57 (br s, 1H, OH). ^{13}C NMR and APT (75 MHz, DMSO-d_6): δ (ppm) = 52.80 (−), 112.50 (−), 119.54 (−), 120.27 (+), 140.59 (+), 143.16 (+), 150.40 (+), 166.69 (+). HR-MS (ESI-): m/z calculated for $[C_8H_6NO_6]^-$ = 212.01951; found 212.02021. RP-HPLC: 16.51 min.

Methyl 2-Hydroxy-4-nitrobenzoate (4). 2-Hydroxy-4-nitrobenzoic acid **1** (4.0 g, 0.022 mol) was dissolved in methanol (60 mL) and concentrated sulfuric acid (4.8 mL) and heated under reflux overnight. The solution was cooled to room temperature, and the yellow solid was filtered and washed well with water to give **4** in 95% yield (4.12 g, 0.021 mol). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 4.03 (s, 3 H), 7.71 (dd, ^3J = 8.69 Hz, ^4J = 2.27 Hz, 1 H), 7.82 (dd, ^4J = 2.27 Hz, ^5J = 0.38 Hz, 1 H), 8.03 (dd, ^3J = 8.78 Hz, ^5J = 0.47 Hz, 1 H), 10.98 (s, 1 H). ^{13}C NMR and APT (75 MHz, $CDCl_3$): δ (ppm) = 53.09 (+), 113.02 (+), 113.49 (+), 117.12 (−), 131.20 (+), 152.08, 161.94 (−), 169.22 (−). HR-MS (ESI-): m/z calculated for $[C_8H_6NO_5]^-$ = 196.02460; found 196.02527. RP-HPLC: 19.07 min.

Methyl 2,5-Bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)-4-nitrobenzoate (6a). To a suspension of methyl-2,5-dihydroxy-4-nitrobenzoate (**3**) (4.27 g, 0.02 mol) and potassium carbonate (16.6 g, 0.044 mol) in dry acetone (100 mL) was added dropwise triethylene glycol bromide (**5**) (10.0 g, 0.044 mol) and heated under reflux and argon atmosphere for 48 h. Acetone was removed under reduced pressure; the residue was dissolved in water and extracted four times with ethyl acetate. The combined organic layers were washed with brine, dried over magnesium sulfate, and evaporated under reduced pressure to give **6a** (9.66 g) as a brown oil containing excess triethylene glycol monomethyl ether. The product was used in the next step without purification. In a small-scale reaction starting from 2 g (0.009 mol), the product was purified by column chromatography on neutral aluminum oxide in hexane:ethyl acetate (gradient from 33% to 100% ethyl acetate) to give pure **6a** (1.5 g, 0.003 mol) in 33% yield. ^{1}H NMR (360 MHz, $CDCl_3$): δ (ppm) = 3.36 (s, 6 H), 3.54 (m, 4 H), 3.60−3.69 (m, 8 H), 3.70−3.77 (m, 4 H), 3.87 (m, 4 H), 3.90 (s, 3 H), 4.19 (t, ^3J = 4.31 Hz, 2 H), 4.24 (t, ^3J = 4.31 Hz, 2 H), 7.49 (s, 1 H), 7.51 (s, 1 H). ^{13}C NMR and DEPT (90 MHz, $CDCl_3$): δ (ppm) = 52.50 (−), 58.93 (−), 69.25 (+), 69.49 (+), 70.19 (+), 70.38 (+), 70.42 (+), 70.47 (+), 70.54 (+), 70.58 (+), 70.91 (+), 70.94 (+), 71.81 (+), 111.52 (−), 118.64 (−), 125.61, 141.88, 145.67, 151.72, 164.90. HR-MS (ESI+): m/z calculated for $[C_{22}H_{35}NO_{12}Na]^+$ = 528.20570; found 528.20496. RP-HPLC: 16.26 min.

Methyl 2-(2-(2-(2-Methoxyethoxy)ethoxy)ethoxy)-4-nitrobenzoate (6b). To a suspension of methyl-2-hydroxy-4-nitrobenzoate **4** (3.40 g, 0.017 mol) and potassium carbonate (13.73 g, 0.1 mol) in dry acetone (100 mL) was added dropwise triethylene glycol bromide **5** (4.32 g, 0.019 mol) and heated under reflux and argon atmosphere for 48 h. Acetone was removed under reduced pressure; the residue was dissolved in water and extracted four times with ethyl acetate. The combined organic layers were washed with brine, dried over magnesium sulfate, and evaporated under reduced pressure. The product was purified by column chromatography in ethyl acetate:hexane (4:1) to give **6b** (2.57 g, 0.007 mol, 41%) as orange oil. R_f = 0.5. ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 3.31 (s, 3 H), 3.45−3.53 (m, 3 H), 3.55−3.65 (m, 7 H), 3.67−3.74 (m, 2 H), 3.85−3.91 (m, 5 H), 4.22−4.28 (m, 2 H), 7.77 (d, ^4J = 1.70 Hz, 1 H), 7.80−7.84 (m, 2 H). ^{13}C NMR and APT (75 MHz, $CDCl_3$): δ (ppm) = 52.30 (−), 58.77 (−), 69.18 (+), 69.40 (+), 70.29 (+), 70.34 (+), 70.38 (+), 70.47 (+), 70.85 (+), 70.96 (+), 71.69 (+), 108.38 (−), 114.94 (−), 126.25 (+), 131.80 (−), 150.36 (+), 158.35 (+), 165.02 (+). HR-MS (ESI+): m/z calculated for $[C_{22}H_{35}NO_{12}Na]^+$ = 366.11649; found 366.11599. RP-HPLC: 16.63 min.

2,5-Bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)-4-nitrobenzoic Acid (7a). **6a** (9.66 g, 0.035 mol) and sodium hydroxide (2.78 g, 0.07 mol) in methanol (100 mL) and water (100 mL) were heated under reflux for 2 h. Methanol was evaporated under reduced pressure, and the residue was extracted with dichloromethane to separate from excess triethylene glycol. Afterward, the aqueous phase was acidified to pH 2 with 5.5 N hydrochloric acid and extracted with dichloromethane four times. The combined organic layers were washed with brine and dried over magnesium sulfate, and the solvent was removed under reduced pressure to obtain **7a** (4.83 g, 0.010 mol, 50% over two steps) as a light brown oil. ^{1}H NMR (360 MHz, $CDCl_3$): δ (ppm) = 3.35 (s, 3 H), 3.36 (s, 3 H), 3.50−3.57 (m, 4 H), 3.58−3.68 (m, 8 H), 3.68−3.75 (m, 4 H), 3.89 (dt, ^3J = 9.42, 4.60 Hz, 4 H), 4.28 (t, ^3J = 4.54 Hz, 2 H), 4.34 (t, ^3J = 4.54 Hz, 2 H), 7.51 (s, 1 H), 7.83 (s, 1 H). ^{13}C NMR and DEPT (90 MHz, $CDCl_3$): δ (ppm) = 58.83 (−), 58.87 (−), 68.39 (+), 69.15 (+), 70.23 (+), 70.32 (+), 70.38 (+), 70.50 (+), 70.63 (+), 70.92 (+), 71.77 (+), 111.38 (−), 119.61 (−), 123.78, 142.19, 146.63, 150.40, 163.95. HR-MS (ESI+): m/z calculated for $[C_{21}H_{33}NO_{12}Na]^+$ = 514.19005; found 514.18890. RP-HPLC: 14.08 min.

2-(2-(2-(2-Methoxyethoxy)ethoxy)ethoxy)-4-nitrobenzoic Acid (7b). **6b** (2.57 g, 0.007 mol) and sodium hydroxide (0.6 g, 0.015 mol) in methanol (100 mL) and water (100 mL) were heated under reflux for 2 h, and the residue was extracted with dichloromethane to separate from excess triethylene glycol. Afterward, the aqueous phase was acidified to pH 2 with 5.5 N hydrochloric acid and extracted with dichloromethane four times. The combined organic layers were washed with brine and dried over magnesium sulfate, and the solvent was removed under reduced pressure to give **7b** (1.78 g, 0.005 mol) in 72% yield as a light brown oil, which solidified upon standing. ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 3.38 (s, 3 H), 3.51−3.59 (m, 2 H), 3.61−3.70 (m, 4 H), 3.72−3.79 (m, 2 H), 3.87−4.06 (m, 2 H), 4.34−4.57 (m, 2 H), 7.79−7.97 (m, 2 H), 8.19 (d, ^3J = 8.50 Hz, 1 H), 9.57 (br s, 1 H). ^{13}C NMR and APT (75 MHz, $CDCl_3$): δ (ppm) = 58.82 (−), 68.36 (+), 69.81 (+), 70.31 (+), 70.34 (+), 70.72 (+), 71.84 (+), 72.33 (+), 108.79 (−), 116.42 (−), 124.93 (+), 133.99 (−), 151.01 (+), 157.70 (+), 164.51 (+). HR-MS (ESI+): m/z calculated for $[C_{14}H_{19}NO_8Na]^+$ = 352.10084; found 352.10046. RP-HPLC: 13.35 min.

Phenyl 2,5-Bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)-4-nitrobenzoate (8a). To 2,5-bis(triethylene glycol)-4-nitrobenzoic acid (**7a**) (1.0 g, 0.002 mol) was added dropwise oxalyl chloride (3 mL) at 0 °C. After complete addition the reaction mixture was stirred at room temperature for 16 h. Oxalyl chloride was removed under high vacuum, and the acid chloride was washed twice with dry dichloromethane. Phenol (0.19 g, 0.002 mol) and triethylamine (0.33 mL, 0.0024 mol) were dissolved in dry dichloromethane (3 mL) and added dropwise to the acid chloride in dichloromethane (5 mL) at 0 °C, after which the solution was stirred at room temperature overnight. The mixture was extracted between dichloromethane and water four times, and the combined organic layers were washed with saturated sodium hydrogen carbonate and brine. The organic phase was dried over magnesium sulfate, and the solvent was removed under reduced pressure to give **8a** (1.05 g, 0.0018 mol, 92%) as a brown oil. ^{1}H NMR (360 MHz, $CDCl_3$): δ (ppm) = 3.35 (s, 3 H), 3.36 (s, 3 H), 3.46−3.56 (m, 4 H), 3.57−3.78 (m, 13 H), 3.89 (br s, 4 H), 4.24 (t, ^3J = 4.54, 4.09 Hz, 2 H), 4.29 (dd, ^3J = 4.54 Hz, 2 H), 7.22 (d, ^3J = 7.72 Hz, 2 H), 7.30 (d, ^3J = 7.72 Hz, 1 H), 7.44 (t, ^3J = 7.72 Hz, 2 H), 7.54 (s, 1 H), 7.71 (s, 1 H). ^{13}C NMR and APT (90 MHz, $CDCl_3$): δ (ppm) = 58.92 (−), 69.30 (+), 69.44 (+), 70.03 (+), 70.42 (+), 70.50 (+), 70.54 (+), 70.87 (+), 70.94 (+), 71.77 (+), 71.78 (+), 111.24 (−), 119.11 (−), 121.46 (−), 124.74 (+), 126.11 (−), 129.48 (−), 142.42 (+), 145.66 (+), 150.52 (+), 152.21 (+), 163.04 (+). HR-MS (MALDI): m/z calculated for $[C_{27}H_{37}NO_{12}Na]^+$ = 590.22135; found 590.22009. RP-HPLC: 20.56 min.

Phenyl 2-(2-(2-(2-Methoxyethoxy)ethoxy)ethoxy)-4-nitrobenzoate (8b). To 2-(triethylene glycol)-4-nitrobenzoic acid (**7b**) (1.0 g, 0.0030 mol) was added dropwise oxalyl chloride (3 mL) at 0 °C. After complete addition the reaction mixture was stirred at room temperature for 16 h. Oxalyl chloride was removed under high vacuum, and the acid chloride was washed twice with dry dichloromethane. Phenol (0.34 g, 0.0036 mol) and triethylamine (0.50 mL, 0.0036 mol) were dissolved in dry dichloromethane (3 mL) and added dropwise to the acid chloride in dichloromethane (5 mL) at 0 °C, after which the solution was stirred at room temperature overnight. The mixture was extracted between dichloromethane and water four times, and the combined organic layers were washed with saturated sodium hydrogen carbonate and brine. The organic phase was dried over magnesium sulfate, and the solvent was removed under reduced pressure to give **8b** (1.2 g, 0.0029 mol, 97%) as a brown oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 3.34 (s, 3 H), 3.47−3.53 (m, 2 H), 3.59−3.63 (m, 4 H), 3.69−3.76 (m, 2 H), 3.92−3.95 (m, 2 H), 4.32−4.35 (m, 2 H), 7.21−7.26 (m, 2 H), 7.27−7.32 (m, 1 H), 7.40−7.48 (m, 2 H), 7.85−7.93 (m, 2 H), 8.06 (d, ^3J = 8.31 Hz, 1 H). ^{13}C

NMR and APT (75 MHz, $CDCl_3$): δ (ppm) = 58.88 (+), 69.24 (−), 69.44 (−), 70.42 (−), 70.51 (−), 70.92 (−), 71.76 (−), 108.41 (+), 115.10 (+), 115.24 (+), 119.92 (+), 121.44 (+), 125.56 (−), 126.09 (+), 129.35 (+), 129.48 (+), 132.40 (+), 150.53 (−), 150.89 (−), 153.72 (−), 156.15 (−), 158.95 (−), 163.23 (−). HR-MS (ESI+): m/z calculated for $[C_{20}H_{23}NO_8Na]^+$ = 428.13214; found 428.13119. RP-HPLC: 21.65 min.

Phenyl 4-Amino-2,5-bis(2-(2-(2-methoxyethoxy)ethoxy)-ethoxy)benzoate (9a). Phenyl 2,5-bis(2-(2-(2-methoxyethoxy)-ethoxy)ethoxy)-4-nitrobenzoate (**8a**) (1 g, 1.76 mmol) was dissolved in ethyl acetate, and palladium on activated charcoal (200 mg, 10%) was added. The reaction was run for 40 h in a hydrogen reactor at 40 °C and 40 bar. After the reaction was complete, the solution was filtered over Celite and washed with ethyl acetate, and the solvent was removed under reduced pressure to give **9a** as light brown oil (0.9 g, 1.67 mmol, 95%). Phenyl 4-amino-2,5-bis(2-(2-(2-methoxyethoxy)-ethoxy)ethoxy)benzoate was highly purified via recycling HPLC in acetonitrile/water (75/25) prior to usage as monomer for polycondensation. ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 3.34 (s, 3 H), 3.38 (s, 3 H), 3.46−3.75 (m, 18 H), 3.77−3.90 (m, 4 H), 4.08−4.20 (m, 4 H), 4.72 (br s, 2 H), 6.33 (s, 1 H), 7.11−7.25 (m, 3 H), 7.32−7.45 (m, 2 H), 7.54 (s, 1 H). ^{13}C NMR and DEPT (75 MHz, $CDCl_3$): δ (ppm) = 58.98 (−), 69.67 (+), 69.71 (+), 69.86 (+), 70.40 (+), 70.49 (+), 70.57 (+), 70.61 (+), 70.87 (+), 71.88 (+), 71.94 (+), 100.66 (−), 106.43, 118.19 (−), 122.09 (−), 125.27 (−), 129.26 (−), 139.40, 144.86, 151.34, 157.18, 163.93. HR-MS (ESI+): m/z calculated for $[C_{27}H_{39}NO_{10}Na]^+$ = 560.24717; found 560.24711. RP-HPLC: 17.46 min.

Phenyl 4-Amino-2,5-bis(2-(2-(2-methoxyethoxy)ethoxy)-ethoxy)benzoate (9b). Phenyl 2-(2-(2-(2-methoxyethoxy)ethoxy)-ethoxy)-4-nitrobenzoate (**8b**) (680 mg, 1.67 mmol) was dissolved in ethyl acetate, and palladium on activated charcoal (130 mg, 10%) was added. The reaction was run for 40 h in a hydrogen reactor at 40 °C and 40 bar. The solution was filtered over Celite and washed with ethyl acetate, and the solvent was removed under reduced pressure to give **9b** as a light brown oil (610 mg, 1.62 mmol, 97%). Before use in polycondensation the product was purified by column chromatography in dichloromethane:methanol (95:5) to give yellow crystals. R_f = 0.3. ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 3.36 (s, 3 H), 3.49−3.56 (m, 2 H), 3.58−3.63 (m, 4 H), 3.71−3.77 (m, 2 H), 3.85−3.92 (m, 2 H), 4.15 (t, ^3J = 5.00 Hz, 2 H), 4.27 (br s, 2 H), 6.23−6.27 (m, 1 H), 6.29 (d, ^4J = 2.27 Hz, 1 H), 7.14−7.25 (m, 3 H), 7.34−7.47 (m, 2 H), 7.91 (d, ^3J = 8.50 Hz, 1 H). ^{13}C NMR and APT (75 MHz, $CDCl_3$): δ (ppm) = 58.89 (−), 68.67 (−), 69.48 (−), 70.33 (−), 70.56 (−), 70.85 (−), 71.80 (−), 99.14 (+), 106.83 (+), 108.04 (−), 115.32, 122.02 (+), 125.20 (+), 129.21 (+), 129.43, 134.68 (+), 151.27 (−), 152.91 (−), 161.70 (−), 163.92. HR-MS (ESI+): m/z calculated for $[C_{20}H_{25}NO_6Na]^+$ = 398.15796; found 398.15760. RP-HPLC: 16.50 min.

Phenyl 4-((4-Methoxybenzyl)amino)-2,5-bis(2-(2-(2-methoxyethoxy)ethoxy)benzoate (10a). To a solution of **9a** (850 mg, 1.58 mmol), *p*-anisaldehyde (320 mg, 2.35 mmol), and acetic acid (0.45 mL, 7.90 mmol) in dry dichloromethane (40 mL) was added sodium triacetoxyborohydride (670 mg, 3.16 mmol), and the solution was stirred overnight at room temperature. The reaction was quenched with saturated $NaHCO_3$ solution and extracted three times with dichloromethane. The combined organic layers were washed with water and dried over magnesium sulfate, and the solvent was removed under reduced pressure. 500 mg of the oily brown product (1.24 g) was purified by recycling HPLC in acetonitrile/water (75/25) to give **10a** (190 mg) as a slightly brown oil in 46% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 3.35 (d, J = 0.38 Hz, 6 H), 3.46−3.54 (m, 4 H), 3.56−3.64 (m, 8 H), 3.64−3.73 (m, 4 H), 3.78−3.87 (m, 7 H), 4.08 (t, ^3J = 5.10 Hz, 2 H), 4.13−4.21 (m, 2 H), 4.37 (s, 2 H), 6.17 (s, 1 H), 6.86−6.89 (m, 1 H), 6.89−6.92 (m, 1 H), 7.14−7.24 (m, 3 H), 7.27 (s, 1 H), 7.28−7.31 (m, 1 H), 7.34−7.43 (m, 2 H), 7.52 (s, 1 H). ^{13}C NMR and APT (75 MHz, $CDCl_3$): δ (ppm) = 46.53 (−), 55.25 (+), 58.96 (+), 69.43 (−), 69.54 (−), 69.64 (−), 69.69 (−), 70.36 (−), 70.50 (−), 70.53 (−), 70.57 (−), 70.83 (−), 71.83 (−), 96.59 (+), 104.53 (−), 114.08 (+), 115.97 (+), 122.07 (+), 125.16 (+), 128.46 (+), 129.20 (+), 130.18 (−), 139.20 (−), 144.85 (−), 151.36 (−), 157.53 (−), 158.91 (−), 164.03 (−). HR-MS (ESI+): m/z calculated for $[C_{35}H_{47}NO_{11}Na]^+$ = 680.30468; found 680.30449. RP-HPLC: 20.66 min.

Phenyl 4-((4-Methoxybenzyl)amino)-2-(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)benzoate (10b). To a solution of **9b** (1.0 g, 2.66 mmol), *p*-anisaldehyde (360 mg, 2.66 mmol), and acetic acid (0.76 mL, 13.3 mmol) in dry dichloromethane (67 mL) was added sodium triacetoxyborohydride (1.13 mg, 5.32 mmol), and the solution was stirred overnight at room temperature. The reaction was quenched with saturated $NaHCO_3$ solution and extracted three times with dichloromethane. The combined organic layers were washed with water and dried over magnesium sulfate, and the solvent was removed under reduced pressure. 480 mg of the viscous light brown product (1.24 g) was purified by recycling HPLC in acetonitrile/water (75/25) to give **10b** (270 mg) as a slightly brown oil in 53% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 3.35 (s, 3 H), 3.47−3.55 (m, 2 H), 3.56−3.64 (m, 4 H), 3.70−3.76 (m, 2 H), 3.82 (s, 3 H), 3.85−3.90 (m, 2 H), 4.14 (t, ^3J = 5.00 Hz, 2 H), 4.32 (d, ^3J = 5.29 Hz, 2 H), 4.64 (s, 1 H), 6.18 (d, ^4J = 2.08 Hz, 1 H), 6.26 (dd, ^3J = 8.69 Hz, ^4J = 2.27 Hz, 1 H), 6.87−6.90 (m, 1 H), 6.90−6.93 (m, 1 H), 7.15−7.25 (m, 3 H), 7.26 (s, 1 H), 7.28−7.30 (m, 1 H), 7.34−7.43 (m, 2 H), 7.94 (d, ^3J = 8.69 Hz, 1 H). ^{13}C NMR and APT (75 MHz, $CDCl_3$): δ (ppm) = 47.02 (−), 55.25 (+), 58.91 (+), 68.65 (−), 69.47 (−), 70.33 (−), 70.54 (−), 70.87 (−), 71.80 (−), 97.05 (+), 104.94 (+), 107.18 (−), 114.12 (+), 122.04 (+), 125.12 (+), 128.66 (+), 129.17 (+), 130.07 (−), 134.58 (+), 144.92, 151.33 (−), 153.48 (−), 159.00, 161.77, 163.90 (−). HR-MS (ESI+): m/z calculated for $[C_{28}H_{33}NO_7Na]^+$ = 518.21547; found 518.21437. RP-HPLC: 23.32 min.

4-Amino-2,5-bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)-benzoic Acid (11). 2,5-Bis(triethylene glycol)-4-nitrobenzoic acid (**7a**) (910 mg, 1.85 mmol) was dissolved in ethyl acetate, and palladium on activated charcoal (136 mg) was added. The reaction was run for 40 h in a hydrogen reactor at 40 °C and 40 bar. After the reaction was complete, the solution was filtered over Celite and washed with ethyl acetate, and the solvent was removed in vacuo to obtain a colorless liquid (850 mg, 1.84 mmol, 99%). ^{1}H NMR (360 MHz, $CDCl_3$): δ (ppm) = 3.32 (s, 3 H), 3.34 (s, 3 H), 3.47−3.54 (m, 4 H), 3.55−3.70 (m, 12 H), 3.73−3.78 (m, 2 H), 3.78−3.85 (m, 2 H), 4.08 (t, ^3J = 4.54, 4.09 Hz, 2H), 4.17−4.20 (t, ^3J = 4.09 Hz, 2H), 6.27 (s, 1 H), 7.45 (s, 1 H). ^{13}C NMR and DEPT (75 MHz, $CDCl_3$): δ (ppm) = 58.75 (−), 68.65 (+), 69.05 (+), 69.27 (+), 69.38 (+), 70.23 (+), 70.33 (+), 70.35 (+), 70.51 (+), 71.66 (+), 71.73 (+), 98.65 (−), 105.58, 116.63 (−), 140.43, 144.58, 154.09, 166.10. HR-MS (ESI+): m/z calculated for $[C_{21}H_{36}NO_{10}]^+$ = 462.23392; found 462.23386. RP-HPLC: 11.34 min.

General Procedure for Polycondensation. Monomer **9a**, **9b**, **10a**, or **10b** (60−100 mg) was dried in a Schlenk tube in high vacuum and transferred into a glovebox under an argon atmosphere. The polymerization was started by fast addition of LiHMDS (1 M in THF, 2.1 equiv for monomers **9a**/**9b**, 1.2 equiv for monomers **10a**/**10b**) to a solution of monomer in dry THF or diglyme (0.5 mol/L). The polymerization was carried out overnight and quenched by addition of saturated aqueous ammonium chloride solution, followed by extraction with dichloromethane. For purification the combined organic layers were washed three times with 1 N NaOH to remove cleaved phenol and once with brine. The organic phase was dried over magnesium sulfate, and the solvent was removed under reduced pressure to yield polymer **13a**, **13b**, **14a**, or **14b**.

13a: ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 3.31 (s, 3 H), 3.34 (s, 3 H), 3.41−3.77 (m, 22 H), 3.79−4.02 (m, 5 H), 4.36 (br. s., 2 H), 4.53 (br s, 2 H), 7.72−7.90 (m, 1 H), 8.54−8.72 (m, 1 H), 10.80 (br s, 1 H). ^{13}C NMR and APT (100 MHz, $CDCl_3$): δ (ppm) = 58.90 (−), 68.96 (+), 69.35 (+), 70.41 (+), 70.45 (+), 70.51 (+), 70.54 (+), 70.61 (+), 71.78 (+), 71.83 (+), 106.52 (−), 114.35 (−), 116.01 (+), 133.98 (+), 142.27 (+), 151.83 (+), 163.52 (+). GPC ($CHCl_3$): M_n 12 100 g/mol, M_w 25 000 g/mol; PDI 2.5. Yield: 60 mg (81%).

13b: Insoluble in organic solvents (DMSO, DMF, THF) and only partly soluble in chloroform, making characterization by NMR

spectroscopy impossible. To facilitate purification, the polymer was not extracted but dispersed in methanol and centrifuged twice to remove cleaved phenol. GPC ($CHCl_3$): M_n 230 000 g/mol, M_w 2 740 000 g/mol, PDI 11.9. Yield: 43 mg (90%).

14a: GPC ($CHCl_3$): M_n 800 g/mol, M_w 1300 g/mol, PDI 1.6. Yield: 60 mg (70%).

14b: ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 3.33 (s, 3 H), 3.51−3.98 (m, 13 H), 4.47−5.20 (m, 2 H), 6.07−6.45 (m, 2 H), 6.79 (d, ^3J = 5.29 Hz, 3 H), 6.97−7.22 (m, 2 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) = 55.18, 58.92, 67.58, 69.16, 70.42, 70.50, 70.61, 71.85, 113.82, 114.27, 115.31, 120.07, 125.37, 129.46, 129.84, 133.20, 143.89, 154.02, 158.85, 167.53. MALDI-ToF: m/z = 7264.5; 18 repeat units calculated for $[C_{396}H_{488}N_{18}O_{109}Na]^+$. GPC ($CHCl_3$): M_n 36 200 g/mol, M_w 83 000 g/mol, PDI 2.3. Yield: 70 mg (95%).

■ CONCLUSIONS

In summary, we have synthesized mono- and bis-TEGylated poly(*p*-benzamide)s of high molecular weights via a lithium amide induced self-polycondensation. The influence of the solvent and the introduction of an N-protective group on the polymerization behavior of different monomers were investigated. Starting from 4-nitrosalicylic acid, a new synthetic route to a bis-TEGylated monomer was developed which opens up opportunities to synthesize many differently bis-substituted polyaramides via the same synthetic strategy. As visualized by TEM, bis-TEGylated poly(*p*-benzamide)s tend to self-assemble via $\pi-\pi$ interactions in the dried state, caused by the perfectly planar and rigidified backbone. However, DLS measurements in chloroform did not indicate the formation of aggregates, revealing molecularly dissolved polymer chains. Poly(*p*-benzamide)s belong to a class of polymers, which is typically characterized by a strong tendency for aggregation through noncovalent interactions. Therefore, the modification with TEG side chains opens the door to new exciting applications through ease of processing and higher solubility. Furthermore, their unique feature of tremendous shape persistence combined with high organosolubility turns these rigid-rod-like polymers into promising building blocks for the formation of nanoscopic objects.

■ ASSOCIATED CONTENT

Supporting Information

Figures S1−S79. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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