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Amphiphilic Invertible Polyurethanes: Synthesis and Properties

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ABSTRACT: We synthesized and characterized novel amphiphilic invertible polyurethanes (AIPUs) that had both hydrophilic (poly(ethylene glycol), PEG) and hydrophobic (polytetrahydrofuran, PTHF) constituents. Two different synthetic approaches produced macromolecules with random and alternating distributions of hydrophilic and hydrophobic fragments along the main backbone. Alternating AIPUs are soluble in both polar and nonpolar organic solvents but are insoluble in water. The insolubility of alternating AIPUs in water can be explained by microphase separation that results in formation of hard segment domains (crystallites) and by strong intermolecular (hydrogen) bonding between urethane groups. In contrast, random AIPUs are soluble in both organic and aqueous media. The environment-dependent formation of AIPU micelles (both random and alternating), whose behavior could be correlated with their chemical structure, has been shown by viscosity measurements and confirmed by ^{1}H NMR spectroscopic study. We foresee that the amphiphilic properties of synthesized polymers will be clearly the basis of new architectures, both in solution and on solid surfaces, and that these polymers have potential uses in a broad range of applications.

Introduction

Amphiphilic molecules, which are molecules with polar and nonpolar moieties, arrange themselves at interfaces and tend to build aggregates in solution.[1] Polymeric surfactants, for example, PEG-based copolymers (e.g., Pluronics), have been studied in a broad range of applications in aqueous environments that include crystallization,[2,3] surface modification for biocompatibility,[4,5] control of particle aggregation in solution,[6,7] and drug delivery.[8] At low polymer concentration, Pluronics exist in solution as isolated polymer coils or unimers even in a very dilute solution.[9−14] As polymer concentration or temperature increases, micelle formation is initiated.[15−21] Further increase in temperature or polymer concentration results in the formation of micellar gels or crystals due to the hydrophobic effect.[22,23] The behavior of amphiphilic copolymers in organic solvents is, in many respects, similar to that of surfactants in water.[24−26] For example, they form micelles and can lower the surface tension at the interface between organic solvents and water.[27,28]

Recently, the focus of research in the field of responsive materials has moved toward the design of polymers with smart behavior. Responsive polymers adapt to surrounding environments, can regulate transport of ions and molecules, change wettability and adhesion of different species on external stimuli, etc.[29] Recently synthesized amphiphilic invertible homopolymers in which each repeating unit contains a hydrophilic and a hydrophobic headgroup have shown a capability of forming environment-dependent micellar or inverse micellar assemblies.[30−32]

Our research group has recently carried out a broad study on synthesis, characterization, and properties of invertible amphiphilic copolymers, polyesters composed of poly(ethylene glycol) (the hydrophilic constituent) and aliphatic dicarboxylic acids (the hydrophobic constituent).[33−42] The most prominent advantages of the resulting amphiphilic invertible polyesters are a rapid inverse switching of macromolecular conformation in response to changes in polarity of the solvent (Figure 1),[33−42] the ability to self-assemble as polymer concentration increases,[36−38,41] and the capacity to encapsulate otherwise insoluble molecules in both polar and nonpolar media.[33,36−39,42] The self-assembled invertible nanostructures with controlled size and morphology are functional in both polar and nonpolar environment and have potential for different applications.[34,35,39−42]

A broad range of potential synthetic copolymers provides opportunities for designing a multitude of different smart materials that vary in length, chemical composition, and chain configuration.[43,44]

Polyurethanes with alternating hydrophilic and hydrophobic fragments segments have demonstrated low surface energies while exposed to air and water; thus, they are believed to exhibit switchable behavior.[45−50] The relationship between surface properties of copolymers containing simultaneously hydrophobic and hydrophilic moieties and the structure of polyurethanes with polyol soft segments has been investigated.[51−54]

Up to now, very few experiments have yet been performed to study the effect of amphiphilic chain composition and the distribution of hydrophilic/hydrophobic fragments on the switching characteristics of macromolecule in response to changes in environmental polarity. Thus, the deep studies aimed at a more in-depth understanding of the formation of invertible micelles in different solvents as well as control of micellar architecture by tuning the distribution and length of hydrophobic/hydrophilic constituents in polymeric backbone remain crucial and timely.

In the present research, we synthesized novel amphiphilic invertible polymers based on PEG as a hydrophilic constituent and PTHF as the hydrophobic portion of the macromolecule. PEG is soluble in both water and nonpolar solvents, whereas PTHF is insoluble in water. Selective common solvents are readily available that would provide micellization and correlate micellar architecture to the composition of AIPUs.

In addition, using PEG (similar hydrophilic sequence to smart polyesters used recently[33−42]) together with more hydrophobic PTHF instead of aliphatic dicarboxylic acid in polyesters provides direct evidence for comparison of polyesters with amphiphilic polyurethanes in terms of effect of composition on surface activity and invertibility.

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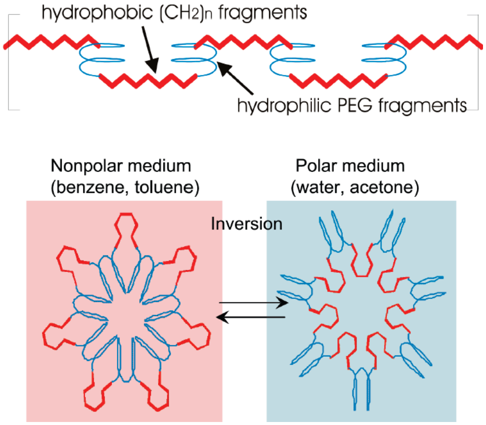

Figure 1. Structure and scheme of a representative amphiphilic invertible polyester micelle in polar and nonpolar media.

Two chain configurations have been developed for amphiphilic polyurethanes with either alternating (PEG-*alt*-PTHF) or random (PEG-*co*-PTHF) distribution of the hydrophilic and hydrophobic fragments. We assumed that we could benefit from the alternating distribution of the hydrophobic and hydrophilic constituents within the main polymeric backbone in terms of rapid switching of the macromolecular architecture in response to changing environmental polarity.[33] The random distribution of the fragments provides polymers with varying lengths of hydrophobic and hydrophilic fragments and, thus, with varying ability to form micelles, to invert, etc.

Experimental Section

Materials. PEG (average molecular weight M_n 600 and 1000 g/mol), Terathane PTHF (M_n 650 and 1000 g/mol), tolylene 2,4-diisocyanate (2,4-TDI), deuterium oxide, and chloroform-*d* were purchased from Aldrich. Benzene-d_6 and acetone-d_6 were purchased from Cambridge Isotope Laboratories, Inc. Toluene, benzene, acetone, and carbon tetrachloride (all ACS grade) were obtained from VWR International. All reagents and materials were used as received.

Characterization. The Fourier transform infrared spectra were recorded with a Nicolet 8700 FT-IR spectrometer (Thermo Scientific) using KBr optical disks.

^{1}H NMR spectra were recorded on a Varian VXR-400 NMR spectrometer using chloroform-*d* and benzene-d_6, as well as mixtures of benzene-d_6−acetone-d_6 (9:1 w/w) and acetone-d_6−D_2O (9:1 w/w) as solvents.

Intrinsic viscosity $[\eta]$ of polymer solutions in acetone and their specific viscosity η_{sp} in a number of solvents, including acetone, toluene (or benzene), a 1:1 mixture of acetone and toluene (or benzene), and carbon tetrachloride, were measured with an Ubbelohde viscometer.

An average molecular weight of synthesized AIPUs was measured by gel permeation chromatography (GPC) using a Waters Corp. modular chromatograph consisting of a Waters 515 HPLC pump, a Waters 2410 refractive index detector, and a set of two 10 μm PL-gel mixed-B columns; the column temperature was set at 40 °C. Tetrahydrofuran (THF) was used as the carrier solvent.

Glass transition and melting temperatures of AIPUs were determined via modulated differential scanning calorimetry (MDSC) using a TA Instruments Q1000 calorimeter. Dry nitrogen with a flow rate of 50 mL/min was purged through the sample. Samples were subjected to an underlying heating rate of 3 °C/min. The temperature was modulated with the amplitude of ±0.64 °C every 40 s.

Synthesis of Alternating AIPUs. A solution of PTHF (0.01 mol) in benzene (60 mL) was refluxed for 3 h with a Dean−Stark trap, and 2,4-TDI (0.02 mol) was then added while stirring. After stirring at 40 °C for 12 h, a solution of PEG (0.01 mol) in benzene (60 mL) was added while stirring. The resulting mixture was stirred for another 12 h at 40 °C. Subsequently, benzene was removed under reduced pressure and residual polymers were dried under vacuum at 60 °C for at least 24 h.

Synthesis of Random AIPUs. A solution of PEG (0.01 mol) and PTHF (0.01 mol) in an aromatic solvent (toluene or benzene) (60 mL) was refluxed for 3 h with a Dean−Stark trap in order to remove residual moisture. Subsequently, 2,4-TDI (0.02 mol) was added while stirring. The mixture was stirred at 40 °C for 12 h, and then toluene was removed under reduced pressure. Residual polymers were dried under vacuum at 60 °C for at least 24 h.

The structure of the synthesized polymers was confirmed by FTIR and NMR spectroscopy (Figure 1S in the Supporting Information). The presence of a urethane group was confirmed by the presence of several characteristic adsorption bands in the FTIR spectrum. The wide adsorption band at 3305 cm^{-1} is caused by valence vibrations of associated amide NH groups. An "amide I" adsorption band is displayed at 1603 cm^{-1}, while an "amide II" band is found at 1537 cm^{-1}. Valence vibrations of the urethane C═O bond result in an intense adsorption band at 1730 cm^{-1}. A doublet of adsorption bands at 1227−1111 cm^{-1} is caused by valence vibrations of urethane and ether C−O bonds. Finally, the presence of 2,4-tolylene moieties was confirmed by the adsorption bands at 848, 955, and 1002 cm^{-1} (out-of-plane and in-plane deformation vibrations of aromatic C−H bonds, respectively), 1353 cm^{-1} (symmetrical stretching of methyl group in tolylene fragment), and 1451 and 1622 cm^{-1} (vibrations of the aromatic ring).

In the ^{1}H NMR spectrum of amphiphilic invertible polyurethane PEG$_{1000}$-*alt*-PTHF$_{650}$ in $CDCl_3$, protons of the hydrophilic poly(ethylene oxide) fragment reveal themselves as peaks at 3.63 ppm (m, 80H, $CH_2OCH_2CH_2OCH_2$) and 3.72 ppm (t, 4H, $C(O)OCH_2CH_2O$) as well as showing a signal at 4.29 ppm (t, 4H, $C(O)OCH_2CH_2O$). The signals of poly(tetrahydrofuran) chains are found at 1.62 ppm (m, 32H, $CH_2OCH_2CH_2CH_2$), 1.75 ppm (m, 4H, $C(O)OCH_2CH_2CH_2$), 3.41 ppm (m, 32H, $CH_2OCH_2CH_2CH_2$), and 4.17 ppm (t, 4H, $C(O)OCH_2CH_2CH_2$). A peak at 2.18 ppm corresponds to protons of the methyl group in a tolylene fragment (s, 6H, CH_3), while a peak at 6.56 ppm is attributed to a nitrogen bound hydrogen atom of the urethane group (s, 4H, NH). Finally, hydrogens of the aromatic ring appear as a series of signals at 6.64−7.69 ppm (m, 6H, C_6H_3). The NMR spectrum of PEG$_{1000}$-*alt*-PTHF$_{650}$ is typical for all synthesized polyurethanes in terms of chemical shifts and multiplicities of proton signals.

Results and Discussion

AIPU Synthesis. Figure 2 shows a two-step procedure for synthesis of AIPUs. In the first step, PTHF has been reacted with a 2-fold molar excess of 2,4-TDI to afford isocyanate-terminated PTHF, a prepolymer for the synthesis of AIPUs. The hydroxy end-groups of PTHF have interacted with one of the isocyanate groups present in 2,4-TDI. Preferably, the isocyanate group in position 4 has reacted with the OH functionality of PTHF due to its higher reactivity in comparison with that of the isocyanate group in position 2.[55] This reaction course has been monitored by FTIR spectroscopy. In the FTIR spectrum of PTHF (Figure 3, curve 1), an absorption band at 3455 cm^{-1} corresponds to the OH stretching vibration. This band is absent in the spectrum of the prepolymer (Figure 3, curve 2), whereas new absorption bands at 2273 cm^{-1} (isocyanate), 1733 cm^{-1} (C═O in urethane), and 3293, 1596, and 1536 cm^{-1} (NH in urethane) have appeared. Given the molar ratio of PTHF:diisocyanate, the above-mentioned difference in the reactivity of isocyanate groups in a 2,4-TDI molecule, and the FTIR spectroscopy data,

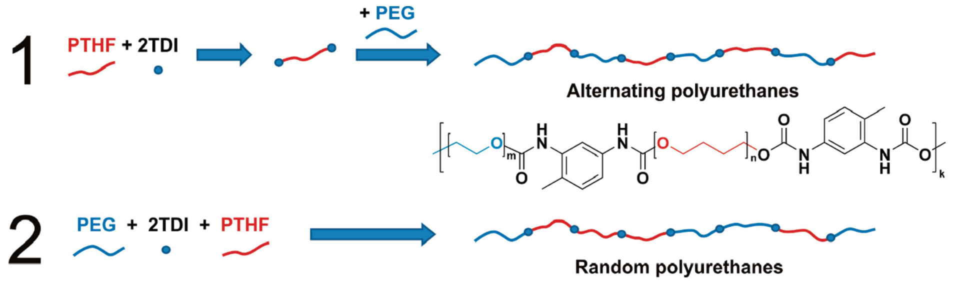

Figure 2. Scheme and reaction of the synthesis of AIPUs.

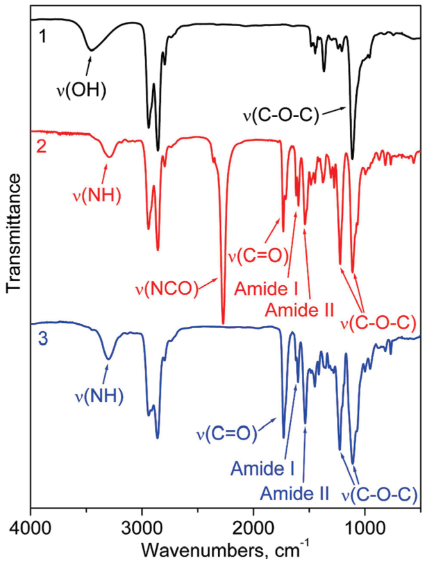

Figure 3. FTIR spectra of (1) $PTHF_{650}$, (2) isocyanate-terminated $PTHF_{650}$, and (3) AIPU (PEG_{1000}-*alt*-$PTHF_{650}$).

we believe that a prepolymer with the structure depicted in Figure 2.1 has been formed.

In the second stage, the prepolymer has been reacted with an equimolar amount of hydroxy-terminated PEG. The isocyanate groups of the prepolymer have interacted with the OH end groups of PEG to give a high-molecular-weight polymer with hydrophilic and lipophilic moieties alternately distributed along a macrochain. The spectrum of the final AIPU (Figure 3, curve 3) shows no absorption bands at 3455 cm^{-1} (OH group) or at 2273 cm^{-1} (isocyanate). A clear increase in intensity (as compared to the prepolymer from the first step) of the absorption bands corresponding to urethane linkages implies the formation of new urethane groups due to the interaction between hydroxy and isocyanate functionalities (Figure 2.1).

Random AIPUs have been synthesized by the reaction of 2,4-TDI with a mixture of PEG and PTHF (Figure 2.2). The molar ratio of the reactants was as 2:1:1, respectively.

The OH group in PTHF is known to display a higher nucleophilicity, and consequently a higher reactivity, toward isocyanates than does the OH group in PEG. We assume that the PTHF molecules are consumed more rapidly during the simultaneous interaction of 2,4-TDI with PEG and PTHF. Although the resultant polyurethanes have a random distribution of hydrophilic and hydrophobic constituents along the macrochain (Figure 2.2), some segments are enriched with PTHF fragments while others are enriched with PEG fragments. Eight AIPUs differing in the length of hydrophilic and hydrophobic fragments and in the type of fragment distribution (alternating or random) have been developed (Table 1).

Table 1. AIPU Characteristics

polymer	m	n	$M_n \times 10^{-3}$, g/mol	$M_w \times 10^{-3}$, g/mol	PDI	$[\eta]$, cm^3/g
PEG_{1000}-*alt*-$PTHF_{650}$	22.3	8.8	13.2	18.2	1.37	22.1
PEG_{1000}-*alt*-$PTHF_{1000}$	22.3	13.6	13.0	17.5	1.35	24.4
PEG_{600}-*alt*-$PTHF_{650}$	13.2	8.8	11.4	16.3	1.42	16.5
PEG_{600}-*alt*-$PTHF_{1000}$	13.2	13.6	10.3	15.1	1.46	17.2
PEG_{1000}-*co*-$PTHF_{650}$	22.3	8.8	11.9	14.9	1.26	20.8
PEG_{1000}-*co*-$PTHF_{1000}$	22.3	13.6	11.2	15.0	1.35	29.3
PEG_{600}-*co*-$PTHF_{650}$	13.2	8.8	11.7	15.3	1.30	16.5
PEG_{600}-*co*-$PTHF_{1000}$	13.2	13.6	10.0	15.8	1.58	11.9

MDSC Study of AIPUs. All synthesized AIPUs are soluble in both polar and nonpolar organic solvents. However, we observed that in contrast to random AIPUs the alternating polymers are not water-soluble. To learn more about AIPU bulk properties, a broad modulated differential scanning calorimetry study was undertaken.

A typical thermogram of the PEG-*alt*-PTHF in the range of temperatures from −100 to 225 °C is depicted in Figure 4 (curve 1, only the total heat flow is depicted). A clear break is seen at ca. −45 °C, indicating the glass transition of the flexible polyol (PEG and PTHF) segments. The glassy state of the soft segments is followed by the development of a semicrystalline state that appears as an exothermic peak at about 0 °C. This process, frequently referred to as “cold crystallization”, is a result of the rearrangement and ordering of nearby segments in the amorphous regions of the polyurethanes in bulk and, obviously, is not accompanied by the ordering of the macromolecules. A further increase in temperature results in the appearance of two endothermic peaks at 16 and 32 °C due to melting of crystallites of the soft polyol segments. These two peaks either imply the melting of two diverse crystalline regions or this can be explained by a different degree of soft segment ordering in the crystallites. The former is more likely. In a separate experiment, a mixture of PEG and PTHF showed two similar peaks in the same region (data not shown). The endothermal peak appearing at 185 °C is attributed to the melting of the hard segment domains formed by 2,4-TDI moieties linked by hydrogen bonding between the urethane groups. Therefore, microphase separation in the PEG-*alt*-PTHF results in appearance of three microphases (Figure 5A).

Thermograms of the PEG-*co*-PTHF (Figure 4, curve 2) are similar to those of the PEG-*alt*-PTHF except for the absence of an endothermic peak at 170−200 °C. Hence, hard 2,4-TDI segments do not form separate domains in the bulk material. Obviously, the reason for this type of behavior is the configuration of the PEG-*co*-PTHF whose macromolecules possess different segments. As a result of random distribution, segments consisting of several PEG fragments and segments with several PTHF fragments are found. These segments apparently form two different crystalline regions (PEG and PTHF domains) with “inclusions” of the hard segments (Figure 5B).

Two AIPUs (PEG_{600}-*alt*-$PTHF_{650}$ and PEG_{600}-*co*-$PTHF_{650}$) do not undergo cold crystallization clearly due to their short fragment lengths (Figure 2S in the Supporting Information). Nevertheless, the endothermic peak at 178 °C indicates the presence of hard segment domains in PEG_{600}-*alt*-$PTHF_{650}$ (Figure 3S in the Supporting Information).

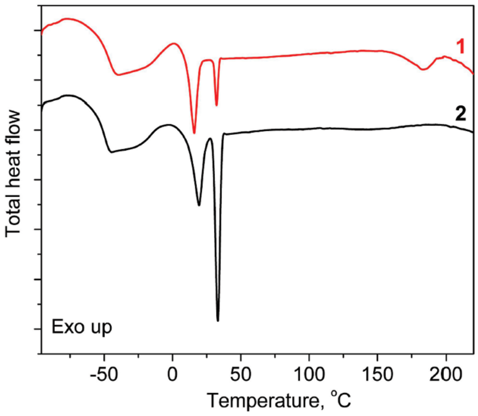

Figure 4. Representative thermograms of the AIPUs: (1) PEG_{600}-*alt*-$PTHF_{1000}$; (2) PEG_{1000}-*co*-$PTHF_{1000}$.

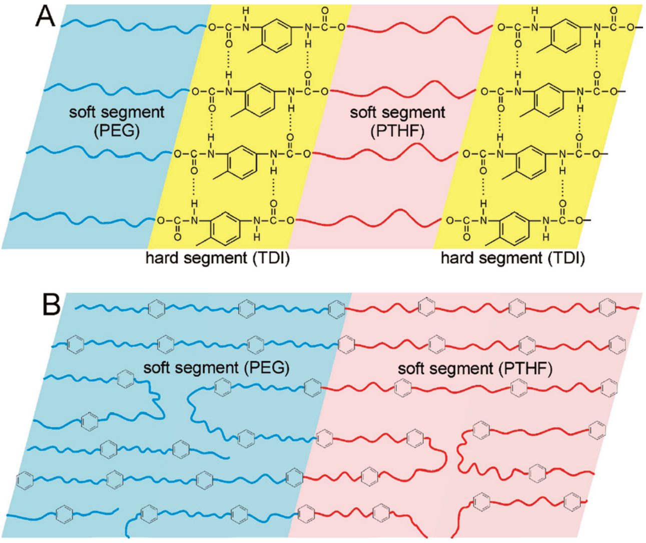

Figure 5. Microphase separation in PEG-*alt*-PTHF (A) and PEG-*co*-PTHF (B).

The formation of hard segments (crystallites) in PEG-*alt*-PTHF and the strong intermolecular bonding between urethane groups in the crystalline domains render the alternating AIPUs insoluble in water.

AIPU Solution Viscosity. Four solvents of varying polarity were selected (Figure 6 and Table 2) to measure specific viscosity of AIPU solutions. Using specific viscosity data, hydrodynamic radii of polyurethane macromolecules in solvents differing by polarity have been calculated (Supporting Information).

The AIPU solutions in tetrachloromethane show the highest specific viscosity, indicating that CCl_4 is a good solvent for extending the conformation of amphiphilic polyurethanes in this medium. In contrast, AIPUs build micelles with PTHF exterior and PEG interior in aromatic solvents, where the lowest specific viscosity has been recorded.

As shown in Table 2, changing solvent polarity leads to changes in the hydrodynamic radius of the AIPU macromolecule in solution. The specific viscosity in a particular solvent depends on AIPU configuration and length of the fragments. Solutions based on polymers with longer PEG/PTHF fragments (PEG_{1000}-*alt*-$PTHF_{1000}$ and PEG_{1000}-*co*-$PTHF_{1000}$) show higher viscosity in a particular solvent, obviously due to flexibility and length of the soft segments and a lower content of hard segments. In contrast, the AIPUs based on PEG_{600} possess the most compact conformation (and, thus, the lowest viscosity) because of a higher content of hard segments and a smaller length of the PEG fragment. Finally, the hydrodynamic radii of the PEG_{1000}-*alt*-$PTHF_{650}$ and PEG_{1000}-*co*-$PTHF_{650}$ are closer to those of PEG_{1000}-*alt*-$PTHF_{1000}$ and PEG_{1000}-*co*-$PTHF_{1000}$. This implies that the length of the PEG fragment has a more substantial impact on macromolecular flexibility than does the PTHF length. Thus, the characteristics of the AIPUs indicate that their invertibility could be correlated with their chemical structure.

Formation of AIPU Micelles and Their Invertibility. In order to confirm formation of AIPU micelles and their invertible behavior, we undertook a broad ^1H NMR spectroscopic study in solvents differing in polarity.

^1H NMR spectroscopy has been extensively used for studying properties of amphiphilic polymers in different media and at wide temperature and concentration range.[56] Recently, we have carried out a broad NMR study on the invertible properties of amphiphilic polyesters to show micellization and self-assembly of these polymers.[41]

In the present study, ^1H NMR spectra of 1% polyurethane solutions have been recorded in a range of solvents differing by polarity, including benzene-d_6 and mixtures of benzene-d_6

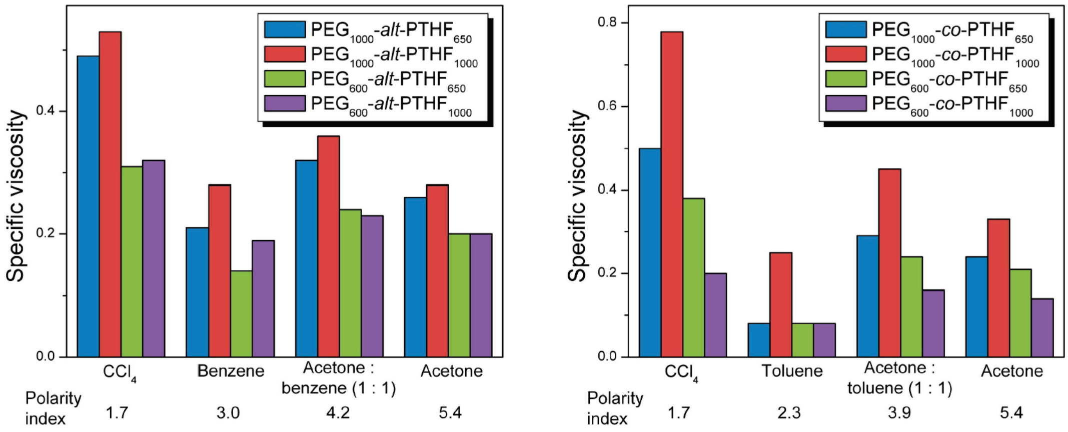

Figure 6. Viscosity data for AIPU solutions in solvents of different polarity (C_{AIPU} = 0.01 g/mL).

and acetone-d_6 (9: 1 w/w, respectively), as well as acetone-d_6 and deuterium oxide (9: 1 w/w) and chloroform-*d* as references (Figure 7). Corresponding peak regions for the random polyurethane PEG$_{1000}$-*co*-PTHF$_{1000}$ can be found in Figure 4S in the Supporting Information.

Both chemical shifts and multiplicity of the proton signals are significantly affected by solvent polarity. In a polar acetone-d_6−D_2O mixture, the signals of both PEG and PTHF protons in the α-position to the urethane fragment (signals a and b, respectively) retain their hyperfine structure, which implies that their motions are not hindered. Peak c, corresponding to the protons in the middle of PEG chain, is narrow, while the signal g of the central methylene groups of the PTHF fragment appears as a broad singlet, indicating that the mobility of hydrophobic PTHF chains is limited. Comparison of spectra recorded in benzene-d_6 and in acetone-d_6−D_2O mixture reveals that peak g in a polar solvent mixture experiences an upfield shift, indicating formation of a nonpolar microenvironment consisting of hydrophobic fragments. The appearance of proton signals in acetone-d_6−D_2O is the result of the polymer micellization. Hydrophobic PTHF chains aggregate and form the dense nonpolar interior of the micelles, while extended PEG fragments become parts of the micellar exterior.

Table 2. Hydrodynamic Radii (nm) of AIPUs in Different Solvents

polymer	CCl_4	aromatic solvent	acetone: aromatic solvent	acetone
PEG$_{1000}$-*alt*-PTHF$_{650}$	5.2	3.9	4.5	4.2
PEG1000-*alt*-PTHF$_{1000}$	5.3	4.3	4.6	4.3
PEG$_{600}$-*alt*-PTHF$_{650}$	4.3	3.3	4.0	3.7
PEG$_{600}$-*alt*-PTHF$_{1000}$	4.2	3.6	3.8	3.6
PEG$_{1000}$-*co*-PTHF$_{650}$	4.9	2.7	4.1	3.8
PEG$_{1000}$-*co*-PTHF$_{1000}$	5.7	3.9	4.7	4.3
PEG$_{600}$-*co*-PTHF$_{650}$	4.5	2.7	3.9	3.7
PEG$_{600}$-*co*-PTHF$_{1000}$	3.7	2.7	3.4	3.3

Comparison of integral intensity of the signals provides important information about the molecular configuration of AIPUs. The ratios of numbers of protons in hydrophobic PTHF and in hydrophilic PEG fragments, calculated from the theoretical composition, as well as the integral intensity of the proton signals in different solvents, are shown in Table 3.

In chloroform-*d* (spectra not shown) all proton signals appear as narrow multiplets, indicating that both hydrophobic and hydrophilic fragments of the chains move freely. For all polymers, the PTHF/PEG proton ratio in chloroform is close to the theoretical value, indicating that no segregation of amphiphilic fragments occurs. In an acetone-d_6−D_2O

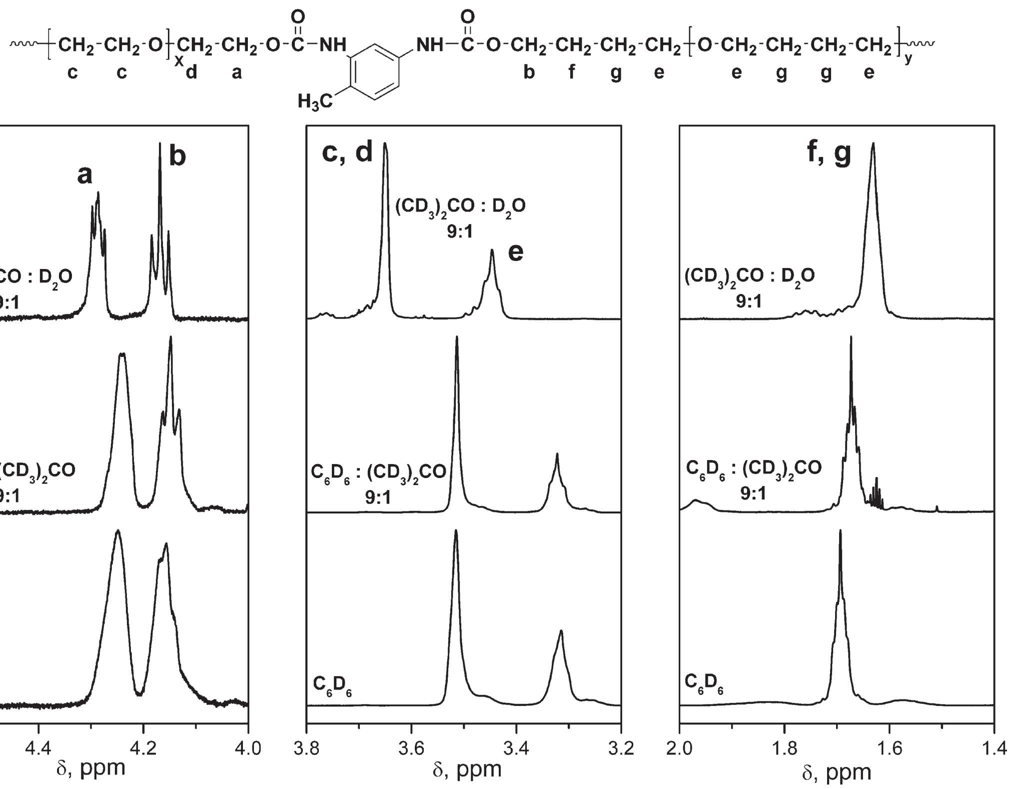

Figure 7. Expanded regions of ^{1}H NMR spectra of PEG$_{1000}$-*alt*-PTHF$_{1000}$ in different solvents.

Table 3. PTHF/PEG Proton Ratio of AIPUs in Different Solvents (Calculated from Integral Values of Proton Peaks in ^{1}H NMR Spectra)

AIPU	PTHF/PEG proton ratio				
	theoretical	$CDCl_3$	C_6D_6	C_6D_6:$(CD_3)_2CO$ 9:1	$(CD_3)_2CO$:D_2O 9:1
PEG$_{1000}$-*alt*-PTHF$_{650}$	0.79	0.85	0.89	0.86	0.75
PEG$_{1000}$-*alt*-PTHF$_{1000}$	1.22	1.26	1.32	1.29	1.17
PEG$_{600}$-*alt*-PTHF$_{650}$	1.33	1.37	1.46	1.38	1.27
PEG$_{600}$-*alt*-PTHF$_{1000}$	2.06	2.11	2.19	2.12	1.99
PEG$_{1000}$-*co*-PTHF$_{650}$	0.79	0.84	0.91	0.86	0.79
PEG$_{1000}$-*co*-PTHF$_{1000}$	1.22	1.26	1.33	1.28	1.14
PEG$_{600}$-*co*-PTHF$_{650}$	1.33	1.38	1.46	1.40	1.29
PEG$_{600}$-*co*-PTHF$_{1000}$	2.06	2.02	2.09	2.00	1.89

mixture, the PTHF/PEG proton ratio is significantly lower than that observed in chloroform-*d*. The integral intensity in the NMR spectrum decreases, which indicates that nonpolar PTHF fragments are screened by the polar PEG chains. This confirms the formation of micelles with a hydrophilic exterior and a hydrophobic interior in a polar medium.

All spectra recorded in benzene-d_6 show a complete disappearance of the hyperfine structure of hydrophilic PEG proton peaks, accompanied by a broadening of the PTHF proton signals. The absence of any signal splitting in the spectra indicates that the movements of both hydrophilic and hydrophobic units are limited due to steric hindrance. The NMR data are fully consistent with the viscosity measurements, since the viscosity of polyurethane solutions in benzene/toluene was the lowest among the solvents tried. Aromatic solvents are poor solvents for amphiphilic invertible polyurethanes, as the polyurethane molecules are shrunken and the polymer chains cannot move freely. We assume that the reason for this behavior is the ability of polyurethanes to form intra- and intermolecular hydrogen bonds. Since benzene molecules do not participate in hydrogen bonding, polyurethane NH groups can interact only with hydrogen bond acceptors present in the macromolecule, namely, the carbonyl group and oxygen atoms of the PEG and PTHF fragments. This then impairs the mobility of the polymer chains. For all of the AIPUs, the values of the PTHF/PEG proton ratios in benzene-d_6 are higher than those observed in chloroform-*d*. Nonpolar PTHF segments form the exterior of the polymer micelle, while polar PEG units are located within the micellar interior.

When 10% acetone-d_6 is added to benzene-d_6, the appearance of NMR signals of hydrophobic protons is changed. Peaks b and g exhibited a signal splitting, which suggested that their mobility had increased. The motions of hydrophilic PEG chains become less limited, as evidenced by the decrease in width of the peaks corresponding to protons c and d. We suggest that since small and mobile acetone molecules possess carbonyl groups that can act as hydrogen bond acceptors, addition of actone-d_6 can break the existing hydrogen bonds between polyurethane macromolecules, thereby facilitating motion of the polyurethane fragments. Since the ratio of hydrophobic to hydrophilic hydrogens in this solvent mixture is similar to that in chloroform, neither of these proton types are screened by the other, obviously indicating that no micelles are formed.

The NMR study therefore confirmed the environment-dependent micellization of AIPUs. Invertible polyurethanes formed micelles with a hydrophobic exterior and hydrophilic interior in a nonpolar (benzene-d_6) solvent. When a small amount of polar (acetone-d_6) solvent is added, it causes a change in polyurethane conformation when polar inner part of the micelle vanishes and PEG chains stretch further into the medium. Introduction of 10% D_2O to acetone promotes formation of micelles with a hydrophilic outer part and a hydrophobic inner part.

Conclusions

We synthesized and characterized novel amphiphilic invertible polyurethanes (AIPUs) with both hydrophilic (poly(ethylene glycol)) and hydrophobic (polytetrahydrofuran) functionalities. Two different synthetic approaches produced macromolecules with random and alternating distributions of hydrophilic and hydrophobic fragments in the main backbone. Solubility of AIPUs can be correlated to their phase behavior in bulk and depends on the length of the hydrophobic and hydrophilic fragments and on the method of synthesis. Alternating AIPUs are soluble in both polar and nonpolar organic solvents but are insoluble in water. Insolubility of alternating AIPUs in water can be explained by microphase separation resulting in formation of hard segments (crystallites) and strong intermolecular (hydrogen) bonding between urethane groups in the crystalline domains. In contrast, random AIPUs are soluble in both organic and aqueous media. Both types of polyurethanes reveal the formation of inverse architectures whose behavior could be correlated to their chemical structure.

The environment-dependent formation of AIPU micelles (both random and alternating) has been shown by viscosity measurements and confirmed by ^{1}H NMR spectroscopic study. In a nonpolar solvent, the micelle exterior is made up of lipophilic PTHF fragments, while the interior consists of the polar PEG fragments. This AIPU structure is inverted in a polar medium, forming micelles with a hydrophobic inner portion and with an outer part made up of PEG fragments.

We foresee that the amphiphilic properties of these polymers could clearly form the basis for new architectures, both in solution and on solid surfaces, which could be used in a broad range of applications.

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Supporting Information Available: Calculation of the hydrodynamic radius of the AIPU macromolecule, FTIR and ^{1}H NMR spectra of the PEG_{1000}-*alt*-$PTHF_{650}$, MDSC thermograms of the PEG_{600}-*alt*-$PTHF_{650}$ and PEG_{600}-*co*-$PTHF_{650}$, microphase separation scheme in the PEG_{600}-*alt*-$PTHF_{650}$ and PEG_{600}-*co*-$PTHF_{650}$, and NMR spectroscopy peak regions of PEG_{1000}-*co*-$PTHF_{1000}$ in different solvents. This material is available free of charge via the Internet at http://pubs.acs.org.

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