A new species of fluorinated polymer surfactant was developed by three component polycondensation analogous to Ugi four-component condensation. The surfactant exhibited unique surface properties, which made cellulose-based materials hydrophobic and decreased the surface tension of CHCl₃. It turned out that the polymer forms micelles in CHCl₃.

Fluorinated surfactants constitute an intriguing class of surfactants, which exhibit high surface activity to not only oil–water interfaces but also gas–liquid and solid–liquid interfaces. The surfactants enable the decrease of surface tension even in organic solvents and the fabrication of superhydrophobic surfaces on substrates, which are adopted in various fields for wetting and repellency applications including paints, coatings, lubricants, fire-fighting foams, and mist suppression. Perfluorooctane sulfonic acid and perfluorooctanoic acid are the most popular members in this class. However, the toxicity and bioaccumulation of the surfactants lead to some inevitable limitations on its use.

Considering the low biocompatibility of such low-molecular-weight surfactants, our recent efforts have been devoted to the development of new entry for polymeric surfactants. Fluorinated polyethers such as oligo(hexafluoropropylene oxide) and poly(perfluoroxytane) are synthesized via the ring-opening polymerization of the corresponding monomers. The vinyl polymer-based surfactants can also be prepared by the radical polymerization of fluorinated vinyl monomers and subsequent functionalization of the polymer terminus with a hydrophilic group. Although these polymeric surfactants become promising candidates as the substitute of low-molecular-weight fluorinated surfactants, two problems on the synthetic methods that have to be solved arise for practical use. One is the low skeletal diversity of polymer surfactants, because the diversity is strongly dependent on the availability of fluorinated monomers. The other problem is a low reproducibility to give a uniform polymer surfactant with precisely same amphiphilicity, owing to the synthetic challenges on the control of polymerization and polymer reaction. Thus, we became intrigued by the potential possibility of multicomponent polycondensation for the creation of fluorinated polymer surfactants bearing well-defined amphiphilicity.

In a recent publication, we reported a one-pot synthetic technique for synthesizing alternating peptides. The technique involves catalyst-free polymerization analogous to the Ugi four-component condensation (Ugi 4CC) for the synthesis of dipeptides. On the basis of our previous method, we planned three-component polycondensation using an aldehyde, perfluoroammonium trifluoromethyltriflate, and a potassium salt of glycine-based ambident molecule bearing both isonitrile and carboxylic acid (CN–CH₂–COOK, 1) to give alternating peptides with perfluoroalkyl pendant groups (Scheme 1). Neutral perfluoroalkylamine can be generated in situ by the treatment of the ammonium salt with 1, which smoothly react with an aldehyde to give the corresponding imine. Further reaction of imine (RC–NR₂) with the ambident molecule would proceed to polymerization, followed by acyl migration to give the alternating peptides without the need of a catalyst. The peptide main chain...
chain is expected to serve as the hydrophilic part of surfactant. Because the alternating peptide skeleton consists of the well-defined repeating unit, the amphiphilicity of the polymer would be precisely controlled by the manipulation of R and RF structures, which could be hardly dependent on the polymerization degree.

Building upon this idea, herein, we describe catalyst-free three-component polycondensation to give perfluoroalkyl-containing alternating peptides. The effects of the polymer structure on their surface-active properties were investigated by surface tension and dynamic light scattering (DLS) measurements. We successfully developed a fascinating polymer surfactant, which made cellulose-based materials hydrophobic and decreased the surface tension of CHCl3. It turned out that the polymer forms thermodynamically stable associates, i.e., micelles in CHCl3.

Fig. 1 depicts the structures of alternating peptides with perfluoroalkyl pendant groups (P1–P6). We selected three types of aldehydes, two perfluoroalkylammonium salts, and potassium isocyanatoacetate (I) as the precursor of the ambient molecule. The ammonium salts were freshly prepared in i-PrOH in situ before the polymerization. According to the schematic illustration in Scheme 1, the three-component polycondensation began with a combination of isobutyraldehyde, C3F7CH2NH3OTf, and I. The three components were stirred in i-PrOH at room temperature for 4 d; then, i-PrOH was removed in vacuo. The residue was stirred for an additional 3 d until the magnetic rotator could no longer be stirred, which produced a highly viscous material. After typical workup, a CHCl3 solution of the products was reprecipitated into hexane to give P1 as a hexane-insoluble part.

The polymer structure of P1 was confirmed by 1H NMR, 13C NMR, 19F NMR, and IR spectra.12 The 1H NMR spectrum was found to consist of proton signals from all the three components with an appropriate integral ratio (Fig. S1†). In the 13C NMR spectrum (Fig. S2†), four amide carbon signals were observed at around 170–180 ppm, strongly supporting the formation of amide linkages in the main chain and the presence of cis-trans rotamers of the N,N-disubstituted amide bond. All carbon signals except for the signals attributed to C3F7 are very sharp, indicating the formation of a high-molecular-weight polymer. The broadening of C3F7 carbons in the range of 100–150 ppm would come from the N,N-disubstituted amide rotamers and multiple scalar couplings between 13C and 19F nuclei. We also measured the 19F NMR spectrum (Fig. S3†),12 which clearly provided the direct evidence for the introduction of 19F nuclei to the polymer skeleton. In the IR spectrum, an amide absorption band was observed at around 1660 cm⁻¹ (Fig. S5†).13 These results clearly indicate that the three-component polycondensation formed an alternating peptide polymer, P1. In a similar manner, using other reaction components, we also prepared the other polymers, P2, P3, P4, P5, and P6. The results are summarized in Table 1. The obtained polymers were hardly soluble in water, while the polymers were soluble in various organic solvents. The weight-average molecular weight (Mw) values were estimated by the diffusion coefficients (D) obtained from diffusion-ordered NMR spectroscopy (DOSY) according to the literature.10,14 The polydispersity indices (Mw/Mn) were estimated by a size exclusion column chromatography. Glass transition temperatures (Tg) were measured by differential scanning calorimetry (DSC) analyses.12 TgS of the alternating peptides were found to be dependent on both the rigidity of the pendant groups (R) and the length of perfluoroalkyl chains, implying that the thermal properties of the polymers would be easily tunable by the selection of appropriate aldehyde and amine components.14

Next, with six types of perfluoroalkyl group-containing peptides, we investigated the surface modification of the polymers on glass plate, filter paper, and cotton gauze (Fig. 2). A water droplet of 6 μL was deposited on each polymer-modified surface to evaluate the water contact angles (WCA).

Table 1  Results of alternating copolymerization

| Polymer | Yielda (%) | Mw b (kDa) | Mw/Mnb | Tgda (°C) |
|---------|-----------|------------|---------|----------|
| P1      | 85        | 7.4        | 1.5     | -23.6    |
| P2      | 82        | 7.8        | 1.8     | -13.3    |
| P3      | 63        | 7.1        | 1.5     | 31.4     |
| P4      | 43        | 7.6        | 1.2     | -1.3     |
| P5      | 67        | 7.4        | 1.3     | 0.7      |
| P6      | 64        | 8.8        | 1.2     | 45.5     |

a Hexane-insoluble part. b Estimated by DOSY spectra (400 MHz, CDCl3, 298 K). c Estimated by a size exclusion column chromatography on the basis of polystyrene standards (eluent: DMF). d Estimated by a differential scanning calorimetry.

By a careful comparison, we found that the IR spectrum of the
modified gauze includes a small shoulder at around 1660 cm\(^{-1}\),
which perfectly matches the amide C=O absorption of \text{P6}. The
other IR absorption signals of the modified gauze almost match
those of the original gauze, suggesting that the high hydro-
phobicity of the gauze is caused by the trace amount of \text{P6}
immobilized on the surface.

The solutions of \text{P1}, \text{P2}, and \text{P3} are transparent, while the
solutions of \text{P4} and \text{P5} are slightly opaque (Fig. 3A), because of
the low solubility of \text{P4} and \text{P5} in CHCl\(_3\). On the other hand, the
solution of \text{P6} is transparent. It is noted that the \text{P6} solution
easily made bubbles by shaking, also indicating the interfacial
activity between CHCl\(_3\) phase and atmosphere. For the evalua-
tion of unique surface modification capability of \text{P6}, the surface
tensions of 1.0 wt\% polymer solutions in CHCl\(_3\) were measured
by the Wilhelmy plate method (Fig. 3B).\(^{16}\) Compared with the
surface tension of pure CHCl\(_3\) (26.9 mN m\(^{-1}\)), those of all
polymers clearly decreased (\text{P1}: 25.7, \text{P2}: 25.5, \text{P3}: 26.7, \text{P4}: 20.9,
\text{P5}: 20.0, and \text{P6}: 22.0 mN m\(^{-1}\)), suggesting that the polymers
serve as a surfactant in CHCl\(_3\).\(^2\) The good contrast between the
organophobicity of perfluoroalkyl pendant groups and the
organophilicity of the main chain would facilitate the interfacial
alignment of the polymers in CHCl\(_3\). The C\(_7\)F\(_{15}\)-containing
polymers (\text{P4}, \text{P5}, and \text{P6}) exhibit higher surface activity than
C\(_2\)F-Containing polymers (\text{P1}, \text{P2}, and \text{P3}).

The effects of alkyl groups (R) in both C\(_7\)F\(_7\)- and C\(_7\)F\(_{15}\)-con-
taining polymer series on the surface activity appear to exhibit a
similar trend as follows; phenyl > i-propyl > biphenyl.

Micellization affects interfacial properties such as reduc-
tion of surface tension. It is therefore, very important to
characterize the surfactants in term of micellization behavior.
Quite reasonably, the critical micelle concentration (CMC),
i.e., onset concentration to form micelle is an important
parameter. Thus, on the assumption, we measured UV-vis
spectra of \text{P6} in CHCl\(_3\) at various concentrations. The UV-vis
spectra include the characteristic absorption to biphenyl
structures in the polymer.\(^2\) We plotted the relationship
between polymer concentration and absorbance at 340 nm
normalized by the concentration (Fig. 4). The plots clearly
include the intersection point at around 0.6 wt\%, indicating
the CMC for the surfactant. To our best knowledge, the studies
on micelle formation in CHCl\(_3\) has not been sufficiently
investigated, while there are several reports about surface
activities of fluorinated surfactants in organic solvents. The
numerical magnitude of CMC of \text{P6} in CHCl\(_3\) might be
comparable with those of typical hydrocarbon- and
fluorocarbon-based low-molecular-weight surfactants in water
(e.g. C\(_8\)H\(_{17}\)COONH\(_4\): 7.0 wt\% and C\(_8\)F\(_{17}\)COONH\(_4\): 0.4 wt\%)\(^4\) suggesting that the perfluoroalkyl pendant groups of \text{P6}
would play an important role on the decrease of surface tension even
in CHCl\(_3\).

To know the size of micelles, we performed the DLS
measurements above the CMC (1.0 wt\%) of the polymer solu-
tions in CHCl\(_3\). In the profile of \text{P6} solution (Fig. 5), we observed

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**Fig. 2** Photographs of 6 \(\mu\)L water droplet on (A) glass plate, (B) filter
paper, and (C) cotton gauze (2 × 2 cm\(^2\)) modified by \text{P6}. Modified glass
and filter paper were prepared by uniformly casting a CHCl\(_3\) solution of
\text{P6} (0.7 wt\%). Modified gauze was prepared by immersing the gauze in
1.0 mL of a CHCl\(_3\) solution of \text{P6} (0.7 wt\%) at room temperature for
3 min, wringing the excess solution, and spray-drying.

**Fig. 3** (A) Photographs and (B) surface tension of 1.0 wt\% polymer
solutions in CHCl\(_3\) at room temperature.

**Fig. 4** Normalized absorbance of \text{P6} at 340 nm (CHCl\(_3\), room
temperature) as a function of concentration (wt%).

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\text{Adv., 2018, 8, 7509–7513} | 7511\]
scattered light signals enough for fitting the auto-correlate function, which reveals the existence of associates in the solution. The size of associates was found to be 9.0 ± 1.2 nm. On the other hand, the other polymers didn’t exhibit any association, which was confirmed by the DLS analyses. It is interesting that P6 forms micelles in CHCl₃, which is a good contrast to the results of P4 and P5 with the same C₂F₁₅ groups.

The differences in the micellization result directly from the bulkiness of the substituents in the peptide main chain, since more bulky groups in the surfactants can stabilize the micelle structure. Probably, the organophobic C₂F₁₅ groups would self-associate in CHCl₃, which could form micelles projecting the organophilic peptide main chain outside. The bulky biphenyl substituents in P6 at the outer face could prevent the aggregation of micelles, probably due to the kinetic suppression of interchain interactions such as hydrogen bondings and fluous-fluorous interactions. In the cases of P4 and P5, lack of appropriate bulkiness could result in the formation of the unstable aggregated structure, leading to the opaque solution as shown in Fig. 3A. The other factors may also play a rule for the formation of superstructure. The micelles in the solution of P6 in CHCl₃ would recognize and coat the hydrophilic cellulose surface, which could make the surface hydrophilic. The biphenyl groups in P6 are also expected to suppress the approach of water not only to the cellulose scaffold but also to the polypeptide main chain of P6 on a molecular scale, which could remarkably decrease the dissolution rate of P6 in a water droplet on the P6-modified surface.

Conclusions

In conclusion, we state that we have developed a new three-component polycondensation technique to synthesize well-defined fluorinated polymer surfactants, where aldehyde, ammonium salt, and potassium salt 1 work as the reaction components. The reaction not only enables the one-pot synthesis of alternating peptides but also enables easy introduction of the perfluoroalkyl group to the polypeptide skeleton at a regular interval. Since the synthesis of alternating copolymers is still difficult, the present method might provide a new insight into the control of polymer sequence. The rigidity of the side group attributed to the aldehyde strongly influences the Tₘ of the polymers. In all polymers, P6 particularly exhibited unique surface activity, which made the cellulose-based materials hydrophobic and decreased the surface tensions of CHCl₃. It was indicated that P6 forms micelle even in CHCl₃, which was confirmed by both UV-vis spectra and DLS measurements. Our finding about micelle formation in organic solvent might open a new field of surfactant chemistry. The effects of polymer structure, solvent, and temperature on the CMC are currently investigating in detail.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was financially supported by JSPS KAKENHI (Grant Numbers JP17H03070 and JP15H00718), Nagase science technology foundation, and Kanamori foundation.

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