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Regioselective Synthesis of Poly(phenylene) as a Complex with Poly(ethylene glycol) by Template Polymerization of Phenol in Water

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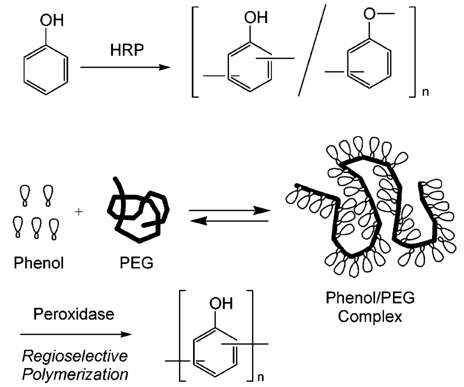
Poly(*m*-phenylene) is one of the most useful polymers for organic polymeric ferromagnets due to their broken conjugation system, which shows higher solubility in organic solvents than linear poly(*p*-phenylene) of comparable molecular weight.[1] The meta linkage of the phenylene rings in the backbone should reduce the extent of delocalization, leading to a blue shift in the emission spectrum.[1,2] Poly(*m*-phenylene)s were prepared by a nickel-catalyzed polymerization of the corresponding aromatic dichlorides.[3,4] These polymers possess a backbone with broken conjugation, showing them to be potential blue and UV emitters.[1,4]

For the past several decades, the great interest of template polymerization[5] has been to synthesize artificial polymers onto matrices and biopolymers onto natural matrices such as DNA or RNA.[6] Template polymerization is usually defined as a process in which monomer units are organized by interactions with a template macromolecule.

Recently, enzymatic syntheses of phenolic polymers have received much attention as an alternate process for preparing conventional phenolic resins without the use of formaldehyde, a monomer for production of conventional phenolic resins (phenol−formaldehyde resins).[7] It was reported that an enzymatic oxidative polymerization of several phenol derivatives produced a new class of polyphenols.[8] From phenol, the simplest and most important phenolic compound in industrial fields, a soluble polyphenol consisting of a mixture of phenylene and oxyphenylene units was synthesized by a peroxidase-catalyzed polymerization in a mixture of methanol and phosphate buffer (Scheme 1).[9] In the enzymatic oxidative polymerization of phenol derivatives, control of the coupling selectivity (regioselectivity) is often very difficult, since the reaction proceeds via coupling of free radical intermediates. In the case of phenol, it was reported that the regioselectivity depended on the mixed ratio of methanol and the buffer in the range of the phenylene content from 40 to 70%. However, the regioselective synthesis of poly(phenylene) or poly(oxyphenylene) from phenol has not been fully achieved yet.[10,11]

The enzymatic polymerization of phenol scarcely proceeds in a buffer.[9] We have found that the addition of poly(ethylene glycol) (PEG) efficiently induced the polymerization in water. Furthermore, the regioselectivity greatly improved to give the polymer mainly consisting of phenylene unit. The present communication describes the peroxidase-catalyzed regioselective polymerization of phenol using PEG as a template.

Scheme 1



We first examined the role of PEG in the polymerization. The change of UV absorption spectra of phenol was observed in the presence and absence of PEG ($M_\mathrm{n} = 2 \times 10^3$) in phosphate buffer (pH 7.0). After adding PEG to the buffer containing phenol, a specific peak around 270 nm increased, suggesting the formation of a PEG−phenol complex by hydrogen-bonding interaction (Figure 1).[12] The intensity of this absorption increased with increasing the weight ratio of PEG to phenol until 1.0, suggesting the hydrogen-bonding interaction of PEG with the hydroxyl group of phenol through a zip mechanism.[5]

Phenol was polymerized using horseradish peroxidase (HRP) as catalyst in phosphate buffer in the presence of PEG at room temperature under air. The polymerization started by the addition of hydrogen peroxide as an oxidizing agent. During the polymerization, powdery precipitates formed, which were collected by centrifugation after the polymerization. ^{1}H NMR analysis showed that the product was a complex of the phenolic polymer and PEG. The PEG amount greatly affected the reaction behaviors (Table 1). In the absence of PEG, the polymer yield was very low (entry 1). The addition of PEG greatly enhanced the polymer yield. In using an excess of PEG, the polymer was obtained almost quantitatively (entries 4−7). In all cases, the unit molar ratio of polyphenol and PEG was ca. 1:1. The molecular weight of the resulting polyphenol was estimated by size exclusion chromatography (SEC) with UV detector (340 nm), in which only the polyphenol was detected (see Supporting Information). The molecular weight of the polyphenol was in the range from 2300 to 2800 and hardly affected the PEG amount. In addition, the polymer formation from phenol in the present reaction system was confirmed by matrix-assisted laser desorption/ionization−time-of-flight mass spectroscopy (MALDI−TOF MS) (see Supporting Information).

The ratio of the phenylene reached around 90%, which was much larger than that obtained in an aqueous methanol (40−70%) solution without PEG.[8] These data suggest that the addition of PEG to the aqueous medium gave poly(*m*-phenylene) regioselectively (Scheme 1).

Figure 2 shows effects of PEG molecular weight on the yield and regioselectivity of the polymer. In the range of the PEG molecular weight from 4×10^2 to 2×10^4, the yield was very high. On the other hand, the yield decreased enormously in the presence of PEG with molecular weight below 3×10^2 and above 1×10^5. The low yield in using low-molecular-weight PEG is probably because the PEG−phenol complex was not formed

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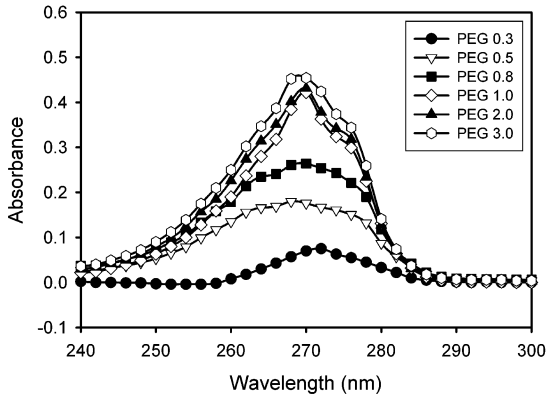

Figure 1. Difference UV absorption spectra of PEG ($M_n = 2 \times 10^3$)−phenol complex with different weight ratios of PEG to phenol amount in phosphate buffer (pH 7.0). Each spectrum was obtained by the subtracting the spectrum of phenol in the absence of PEG from that in the presence of PEG. The numbers in the legend in the figure are weight ratios of PEG to phenol.

Table 1. Polymerization of Phenol with Different PEG Amounts[a]

entry	PEG (g)[b]	yield (%)[c]	M_n[d]	composition ratio (polyphenol:PEG)[e]	Ph/Ox[f]
1	0	≤3			
2	0.1 (0.45)	44	2800	1:1.02	93/7
3	0.2 (0.91)	83	2300	1:1.02	95/5
4	0.3 (1.4)	95	2500	1:1.03	92/8
5	0.4 (1.8)	95	2400	1:1.04	90/10
6	0.5 (2.3)	96	2300	1:1.00	88/12
7	0.7 (3.6)	96	2300	1:1.00	88/12

[a] Polymerization of phenol (0.47 g, 5.0 mmol) using HRP catalyst (2.0 mg) in the presence of PEG ($M_n = 2 \times 10^3$) in 0.1 M phosphate buffer (pH 7.0) at room temperature under air. [b] In parentheses, molar ratio of monomer unit of PEG for phenol. [c] Yield of polyphenol based on phenol in the complex product, determined by ^{1}H NMR spectroscopy. [d] Determined by SEC using DMF as eluent with polystyrene standards. [e] Molar ratio of monomer unit between polyphenol and PEG determined by ^{1}H NMR spectroscopy. [f] Unit ratio of phenylene/oxyphenylene (Ph/Ox) determined by titration of hydroxyl group.

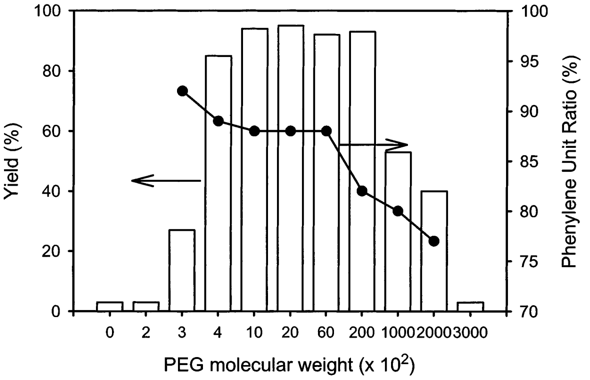

Figure 2. Effect of molecular weight of PEG on polymer yield and structure.

efficiently. The gelation and/or large increase of the solution viscosity were observed by the addition of high-molecular-weight PEG solution to phenol, which prevents the efficient polymer production.

The complex formation between the resulting polyphenol and PEG by hydrogen-bonding interaction was confirmed by FT-IR (see Supporting Information). A peak at 3366 cm^{-1} due to self-associated phenolic O−H group was shifted to 3289 cm^{-1}, ascribed to phenolic O−H hydrogen-bonded with PEG.[13] In the DSC chart of the complex (see Supporting Information), no melting point due to PEG was observed. A single glass transition temperature was seen at 44 °C, lower than that of the polyphenol synthesized in an aqueous methanol without PEG[9] (61 °C). These data clearly indicate that there exists rather strong intermolecular interaction between both polymers in the complexes,[14] and they are fully miscible with each other in a homogeneous amorphous phase.

In conclusion, the enzymatic oxidative polymerization of phenol was achieved in water, which proceeded regioselectively in the presence of PEG. During the polymerization, polyphenol was produced in high yields as a precipitate complexed with PEG. The presence of the PEG template in an aqueous medium greatly improved the regioselectivity of the polyphenol with the phenylene unit content higher than 90%. The FT-IR and DSC analyses exhibited the formation of the miscible complex of polyphenol and PEG by hydrogen-bonding interaction. The present study clearly shows that the carbon−carbon coupling between phenolic radical intermediates regioselectively takes place in the presence of PEG in water, yielding poly(*m*-phenylene). Furthermore, the lack of organic solvents in the present reaction system is environmentally friendly. Further investigations on synthesis of new polymeric materials by the regioselective polymerization of phenol derivatives using water-soluble polymers as a template are under progress in our laboratory.

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Supporting Information Available: Text describing the polymerization procedure, materials, FT-IR, DSC, SEC, and MALDI−TOF MS charts. This material is available free of charge via the Internet at http://pubs.acs.org.

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