Synthesis of Network Polymers from Multifunctional Aromatic Thiol Compounds

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Network polymers have been synthesized by means of catalysis free thiol-yne reaction of multi-functional aromatic ethynyle and thiol compounds, 1,3,5-trithiynylbenzenen (TEB), 1,4-diethynylbenzenen (DEB), 1,4-benzenedithiol (BDT) and benzenethiol (BT). The network polymers of TEB/DEB-BDT or TEB-BDT/BT were obtained in good yields. The feed ratio of DEB or BT increased the chloroform solution, fragments, of the network polymers. The fragments of the network polymers showed optical properties derived from conjugation units of phenyl-ethynyl-sulfide. The network polymers have been synthesized by oxidation reaction of multi-functional aromatic thiol compounds, 1,3,5-benzene trithiol (BTT) with BDT or 4,4’-biphenyl diithiol (BPDT), accompanied by formation of disulfide bonds. The BTT network was degradable by a reductant, tris(2-carboxyethyl)phosphine hydrochloride.

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tetrahydrofuran (THF)

Scheme 2. Synthesis of disulfide crosslinked network polymer by oxidation reaction of BDT-BDT, BPDT.

sulfoxide (DMSO, Kanto Chemical Co., Inc.), methanol (MeOH, Kanto Chemical Co., Inc.), and chloroform (Kanto Chemical Co., Inc.) were commercially obtained from Kanto Chemical Co., Inc., and used as received.

Synthesis of TEB-BDT based network polymers.—The molar ratio of ethynyl group in TEB and/or DEB to S-H group in BDT and/or BT was adjusted to 1.0. TEB (0.1 mmol), BDT (0.15 mmol), and THF (1.0 mL) were added to a 20 mL vial. The reaction stirred at room temperature for 24 h. The reaction mixture was poured into large excess of MeOH, and the precipitate was corrected by filtration, then washed with MeOH for several times. The obtained polymer was dried in vacuo. at room temperature for 6 h. TEB/DEB-BDT network polymers and TEB-BDT/BT network polymers were synthesized by the same procedures.

Synthesis of BTT-based network polymers.—BTT (1.03 g) and DMSO (0.327 mL) were introduced to a 10 mL ample tube. After the ample tube was sealed by burning off, the reaction system was heated at 50°C for 10 min. The reaction mixture was poured into large excess of MeOH, and the precipitate was corrected by filtration, then washed with MeOH for several times. The obtained polymer was dried in vacuo. at 60°C for 6 h. BTT-BDT/BPDT network polymer were synthesized by the same procedures.

Reductive degradation of the network polymers.—BTT network polymer was stirred in FOCUS Protein Reductant (42 μL (TCPE: 0.19 mol/L) with the supplied buffer, pH 7.2, at room temperature for 24 h. The reduction with DTT was investigated in THF solution of DTT (0.19 mol/L) in the same way for 7 days at room temperature.

Analytical procedures.—FT-IR spectra of network polymers were recorded on a Jasco FT/IR-410 (JASCO Corporation). The samples were prepared as KBr tablets, and 30 scans were accumulated from 4000 to 500 cm⁻¹. ¹H NMR spectra of linker molecules or reaction systems (solution samples) were recorded on a JEOL-JNM-LA300 spectrometer in pulse Fourier transform mode. Molecular weight and molecular weight distribution of the polymers were measured at 40°C by means of gel permeation chromatography (GPC), Shimadzu Prominence GPC System, using chloroform as solvent and calibrated with standard polystyrene samples. UV-vis absorption spectroscopy of the chloroform soluble faction of the network polymer was conducted with Shimadzu UV-1600PC. Photoluminescence (PL) spectrum of the solution was recorded on a Shimadzu RF-1500, exited at the maximum absorption wave length of the solution sample.

Results and Discussion

TEB/(DEB)-BDT/(BT) network polymers.—The TEB/DEB-BDT network polymers were synthesized by the catalyst free thiol-yne reaction of TEB, DEB and BDT in THF at room temperature. The

| Run | TEB (mmol) | DEB (mmol) | BDT (mmol) | Yield (%) | CHCl₃ sol.² (wt%) | Mₕ ³ | Mₜ/Mₕ ³ | λmax ⁴ (nm) | UV-vis ³ (nm) | PL ³ (nm) |
|-----|-----------|------------|------------|-----------|------------------|------|---------|------------|--------------|------------|
| 1   | 0.100     |            | 0.150      | 90.8      | 10.8             | 560  | 1.9     | 315        | 448          |
| 2   | 0.090     | 0.010      | 0.145      | 84.7      | 17.7             | 560  | 6.7     | 316        | 446          |
| 3   | 0.075     | 0.025      | 0.138      | 70.5      | 28.0             | 520  | 2.6     | 321        | 435          |
| 4   | 0.050     | 0.050      | 0.125      | 69.6      | 35.3             | 480  | 1.6     | 345        | 444          |
| 5   | 0.025     | 0.075      | 0.113      | 85.6      | 28.0             | 840  | 1.8     | 342        | 457          |
| 6   | 0.010     | 0.090      | 0.105      | 89.9      | 35.3             | 480  | 1.6     | 345        | 444          |
| 7   | 0.100     | 0.100      | 0.100      | 63.3      | 72.0             | 510  | 1.6     | 348        | 445          |

²CHCl₃ soluble fraction,
³molecular weight and molecular weight distribution of CHCl₃ soluble fraction,
⁴maximum absorption peaks (λmax) in the UV spectroscopy and PL spectroscopy of CHCl₃ soluble fraction.
The results are summarized in Table I. The polymers were obtained in good yield as precipitated powders, which were not swollen in any solvents. Characterization of the insoluble polymer networks is difficult, and we focused on the structure of the liner (branched) and/or low molecular weight fractions of the obtained polymers, which were soluble in some organic solvents. In this experiment, chloroform was selected as the solvent due to the high solubility of the polymer fractions. Figure 1a shows relationship between DEB feed ratio and wt% of chloroform soluble fraction of the resulting polymers. The chloroform soluble fraction increased with increasing the feed ratio of DEB. Increase of the DEB should increase the linearity of the resulting polymer, as shown in Scheme 3. Molecular weights of the chloroform soluble fractions were lower than 1000, indicating formation of network fragment. TEB-BDT/BT network polymers were also synthesized by the same way. The results are summarized in Table II. Figure 1b shows relationship between BT feed ratio and wt% of chloroform soluble fraction of the resulting polymers. The chloroform soluble fractions, whose molecular weights were less than 1000, increased with increasing the feed ratio of BT. Increase of the BT should increase fragmentation degree of the network polymer, as shown in Scheme 4. 

**Scheme 3. Model of formation of TEB/DEB-BDT network polymer.**

1H NMR spectrum of the chloroform soluble fraction of the polymer obtained in run 2 showed peaks at 7.2, 6.2, and 3.6 ppm derived from phenyl group, unsaturated moiety, and thiol group, respectively. The chloroform solutions of other TEB/DEB-BDT network polymers and TEB-BDT/BT network polymers showed the similar peaks in their spectra.

Optical properties of the chloroform solutions of TEB/DEB-BDT and TEB-BDT/BT network polymers were investigated with UV-vis and PL spectroscopy. UV and PL spectra of TEB/DEB-BDT (run 5) and TEB-BDT/BT (run 9) network polymers are shown in Figures 2a and 2b, respectively. The maximum absorption peaks ($\lambda_{\text{max}}$) in the UV spectroscopy and PL spectroscopy are summarized in Table II. The chloroform solutions of the network polymers showed UV spectra with an absorption peak at about 360 nm, which should be derived from $\pi-\pi^*$ transition. The wave length was blue shifted in comparison with that of the phenylene-vinylene based polymers. Existence of sulfide in the $\pi$-conjugation would cause the shift of the absorption peak. The wave length of $\lambda_{\text{max}}$ increased with increasing DEB feed ratio in the TEB/DEB-BDT network polymers. Increase of the DEB feed ratio would increase the linearity of the resulting polymer, which increased the wave length of $\lambda_{\text{max}}$ in the UV spectra. By contrast, the wave lengths of $\lambda_{\text{max}}$ of the TEB-BDT/BT network polymers were almost independent of the BT feed ratio, indicating degree of the fragmentation of the network would not affect the wave length of the UV spectra.

![Figure 1. Relationship between (a) DEB feed ratio or (b) BT feed ratio and chloroform soluble fraction (wt%) of the resulting polymers.](image)

**Table II. Synthesis, structure, and property of TEB-BDT/BT network polymer.**

| Run | TEB (mmol) | BDT (mmol) | BT (mmol) | Yield (%) | CHCl$_3$ sol.$^a$ (wt%) | $M_n$.$^b$ | $M_w/M_n$.$^b$ | $\lambda_{\text{max}}$ | UV-vis.$^c$ (nm) | PL.$^c$ (nm) |
|-----|------------|------------|-----------|-----------|------------------------|----------|----------------|----------------|----------------|-------------|
| 8   | 0.095      | 0.135      | 0.015     | 91.1      | 12.0                   | 600      | 2.1            | 314            | 429            |
| 9   | 0.0875     | 0.113      | 0.0375    | 79.6      | 62.5                   | 560      | 1.5            | 315            | 413            |
| 10  | 0.075      | 0.075      | 0.075     | 76.2      | 62.5                   | 580      | 1.6            | 325            | 420            |
| 11  | 0.0625     | 0.0375     | 0.113     | 97.7      | 73.9                   | 270      | 1.7            | 321            | 433            |
| 12  | 0.055      | 0.015      | 0.135     | 95.5      | 88.2                   | 340      | 2.0            | 313            | 430            |

$^a$CHCl$_3$ soluble fraction,

$^b$molecular weight and molecular weight distribution of CHCl$_3$ soluble fraction,

$^c$maximum absorption peaks ($\lambda_{\text{max}}$) in the UV spectroscopy and PL spectroscopy of CHCl$_3$ soluble fraction.
PL spectra of the chloroform soluble fraction of the network polymers were acquired exited at the $\lambda_{\text{max}}$ in the UV spectra. The fractions of TEB/DEB-BDT network polymers showed the peak ($\lambda_{\text{max}}$) at around 440–460 nm, which were larger than those of the TEB-BDT/BT network polymers, 410–430 nm. The difference in the $\lambda_{\text{max}}$ would be derived from linear $\pi$-conjugation length of the fractions.

**BTT(-BDT, BPDT) network polymers.**—BTT, BTT-BDT, and BTT-BPDT network polymers were synthesized by the oxidation reaction in (with) DMSO at 50°C for 10 min. The network polymers were obtained quantitatively as white powders (Figure 4a). Figure 3 shows FT-IR spectra of BTT monomer and BTT network polymer. Intensity of the absorption peak at 2560 cm$^{-1}$ derived from thiol group of BTT decreased, and the peak at 530 cm$^{-1}$ derived from disulfide bond newly appeared in the spectrum of the BTT network polymer. These results indicate formation of network polymer by the disulfide bond derived from oxidation of thiol groups. The FT-IR spectroscopy of BTT-BDT and BTT-BPDT network polymers showed similar changes in the spectra. In the case of the reaction of non-aromatic thiol compounds, the reaction at 85°C for 8 h is necessary to obtain the network polymer. The high reactivity of the aromatic thiol compounds should make it possible to obtain the network polymer under lower temperature and shorter reaction time.

The network polymers are stable against normal light or UV irradiation. Reductive degradation of the BTT network polymer was investigated by TCEP and DTT at room temperature. The degradation
Figure 4. Photos of degradation process of BTT network polymer, (a): before reducing, (b): after reducing by TCEP for 24 h in buffer, (c): after reducing by DTT for 7 days in THF.

with TCEP in the buffer turned to the solution for 24 h, as shown in Figure 4b, indicating degradation of the network polymer by reduction of disulfide bonds. By contrast, the network polymer in THF solution with DTT remained solid, as shown in Figure 4c. These results can be explained by low reduction ratio of the disulfide bonds in the network. In the case of the reduction with DTT, two types of DTT, oxidized and reduced DTT, would co-exist in the reaction system. The $pK_a$ value of the aromatic thiol BTT is 5.2, which is smaller than that of DTT, 14.5. The reduced BTT would be re-oxidized by oxidized DTT under the conditions, and the network structure should be remained in spite of the long reaction time. By contrast, TCEP did not play a role of the oxidant, and should promote reduction of the disulfide bonds in the network structure. The BTT-BDT, and BTT-BPDT network polymers were also completely degradable by TCEP.

Conclusions

The network polymers were successfully synthesized by non-catalytic thiol-yne reaction of multifunctional aromatic thiol compounds. The TEB/DEB-BDT and TEB-BDT/BT network polymers were obtained in good yields. The feed ratio of DEB or BT increased the chloroform solution of the network polymers, which showed optical properties derived from the $\pi$-conjugation in the network structure. Increase of the linearity of the network polymer, by increase of DEB feed ratio, increased the absorption and emission wave length in the chloroform soluble fraction of TEB/DEB-BDT network polymer. Oxidation of BTT in DMSO yielded the network polymer by formation of the disulfide bond. The network polymer was degradable by reduction with TCEP.

The multifunctional aromatic thiol compounds should be usable monomers to synthesize the network polymers using thiol-yne and oxidation reactions. Combination of functional monomers with the aromatic thiol compounds would make it possible to synthesize the network polymer with high performance. Addition of hydrophilicity to the network polymer with residual aromatic thiol groups would be applicable for medical use. For examples, visualization of biological redox reaction in the peptide and protein chemistries. We are planning to synthesize highly functionalized network polymers using thiol-yne reaction, and the results will be reported elsewhere.

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