Formation of Self-healing Supramolecular Materials Using Inclusion Complexes between Cyclodextrin and Hydrophobic Guest Groups

A Doctoral Thesis

by

Takahiro Kakuta

Submitted to

the Graduate School of Science, Osaka University

February, 2014

Acknowledgements

This work was carried out from 2011 to 2014 under the supervision of Professor Dr. Akira Harada at the Department of Macromolecular Science, Graduate School of Science, Osaka University. The author would like to express his sincere gratitude to Professor Dr. Akira Harada for his guidance and assistance throughout this study. Grateful acknowledgements are made to Assistant Professor Dr. Yoshinori Takashima for his continuing help.

The author is also grateful to Professor Dr. Hiroyasu Yamaguchi, Associate Professor Dr. Akihito Hashidzume, Dr. Yuichiro Kobayashi, Dr. Takashi Nakamura, Mrs. Miyuki Otsubo, Dr. Yongtai Zheng, Mr. Masaki Nakahata, Ms. Tomoko Sekine, Mr. Kazuhisa Iwaso, Mr. Chun-Yen Liu, Mr. Lee Isaac Eng Ting, and Mr. Takaaki Sano, for their helpful suggestion and all the members of Harada laboratory for their cooperation and friendship.

Grateful acknowledgements are also made to Professor Dr. Tadashi Inoue for dynamic viscoelastic measurement, Mr. Seiji Adachi and Dr. Naoya Inadumi for NMR measurement, and Dr. Akihiro Ito for SEM experiments.

The author appreciates the financial support from JST-CREST (Japan Science Technology, Core Research of Excellence Science Technology) (May, 2010-present).

Finally, the author would also like to express his heartfelt thanks to his parents, Kenji Kakuta, Yumiko Kakuta, and his sister, Reiko Kagoshima for their help and encouragements.

February, 2014

角田 貴洋

Takahiro Kakuta

Contents

Chapter 1

General Introduction

1-1. Supramolecular chemistry

Supramolecular Chemistry has been defined by one on its leading proponents, Charles J. Pedersen, Donald J. Cram, and John –M. Lehn, who won the Nobel Prize for their work in the area in 1987[1-4]. The field of supramolecular chemistry was inspired by the "receptor" concept propounded by Emil Fischer et al.[7-9] (Figure 1-1). This concept depicts "lock and key" mechanism, which was represented by stereoscopic-matched configuration, and geometric complementarity under molecular recognitions. Moreover, supramolecular system, such as the biological system, exhibits selectivity and high efficiency due to supramolecular interactions. These properties were needed to control non-covalent bonds ((1) ionic interaction[10], (2) ion-dipole interaction[11], (3) dipole-dipole interaction[12], (4) hydrogen bond[13], (5) cation-π interaction[14], (6) π-π interaction[15], (7) van der Waals force and (8) hydrophobic effect[16], and so on) within given molecules limits. Thus, supramolecular chemistry was developed for discussing non-covalent bonds.

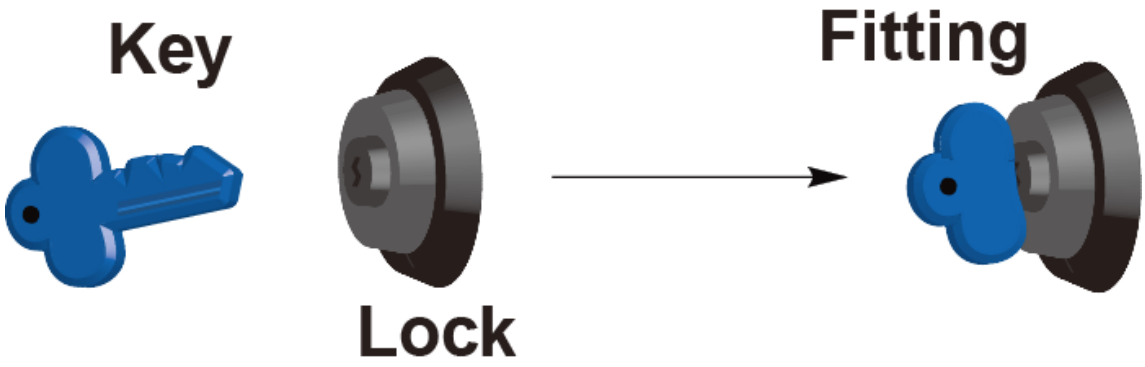


Figure 1-1. Conceptional illustration of molecular recognition.

1-2. Cyclic host molecules

Crown ethers[17-18] and cryptands[19-20] selectively bind with alkali metal cations (Figure 1-2). Recently, there are many report of complex formations with cyclic host molecules using cyclodextrins (CD)[21-22], calixarenes[23-25], pillararenes[26-27] and cyclophanes[28-29]. Molecular recognition using these cyclic host molecules becomes a new-chemistry-studied field[30].

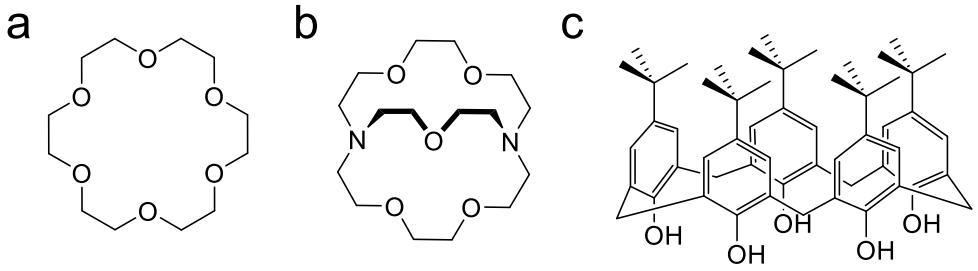
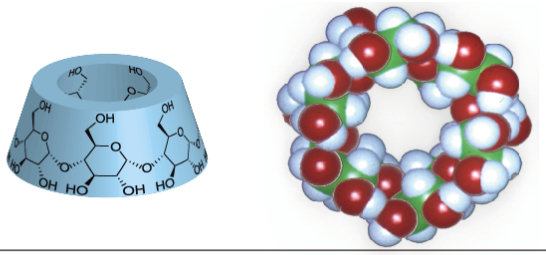
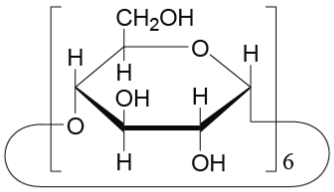


Figure 1-2. Chemical structures of (a) crown ether, (b) cryptand and (c) calixarene.

Cyclodextrins[31-32] are cyclic oligosaccharides comprising D-glucopyranoside units, linked by a 1,4-glycosidic bond. The three most important members of cyclodextrin (CD) family are α-cyclodextrin (α-CD), β-cyclodextrin (β-CD), and γ-cyclodextrin (γ-CD), which possess, respectively, six, seven, and eight glucopyranoside units. The shape of a cyclodextrin is often represented as a tapering torus or truncated funnel. CDs have two different faces to the cyclodextrin. The exterior of CDs comprises the hydroxyl groups and exhibits hydrophilic properties. In contrast, the interior of CDs consists of hydrogen molecules and exhibits hydrophobic properties. In aqueous media, CDs, as host molecules, can selectively include the appropriate hydrophobic guest compounds that match their hydrophobic cavity sizes[33]. (Figure 1-3) Therefore, CDs possess vast industrial applications, such as in the food, cosmetics and pharmaceutical sectors.





	αCD	βCD	γCD
No. of Glucose Units	6	7	8
Diameter of Cavity (nm)	0.47	0.60	0.75
Height of Torus (nm)	0.79	0.79	0.79

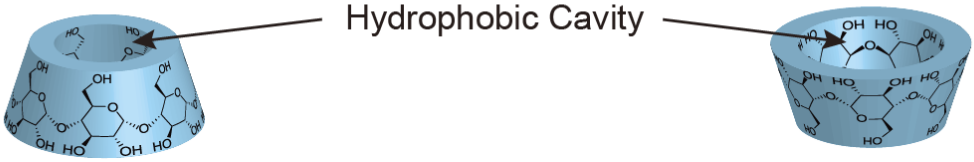


Figure 1-3. Properties and chemical structures of cyclodextrins.

1-3. Helical supramolecular polymers

Molecular recognition was pointed out as the essence of supramolecular chemistry[34]. Hence, many scientists focused on the non-covalent bonds for creating artificial DNA helical structure, bio-inspired catalysis, system of light energy conversion, and supramolecular materials.

In the study of artificial DNA helical structure, J. -M. Lehn et al. reported the spontaneous formation of a double helix structure by oligobipyridine ligands, containing two and three 2,2´-bipyridine subunits separated by 2-oxapropylene bridges with suitable metal ions. They suggested that this phenomenon opens the way to design and study self-assembling systems (Figure 1-4). [35-36]

In the bio-inspired catalysis, M. L. Bender et al. estimated the effect of combination of imidazolyl and carboxyl groups upon the cleavage of *m*-*t*-butylphenyl acetate in the presence of α-CD. They studied that the mechanism of the combination of the imidazolyl, carboxyl, and hydroxyl groups is apparently different from those shown by the “charge-relay”

system in enzymatic reactions.[37] R. Breslow et al. extended the use of CDs with two imidazole groups as enzyme models[38].

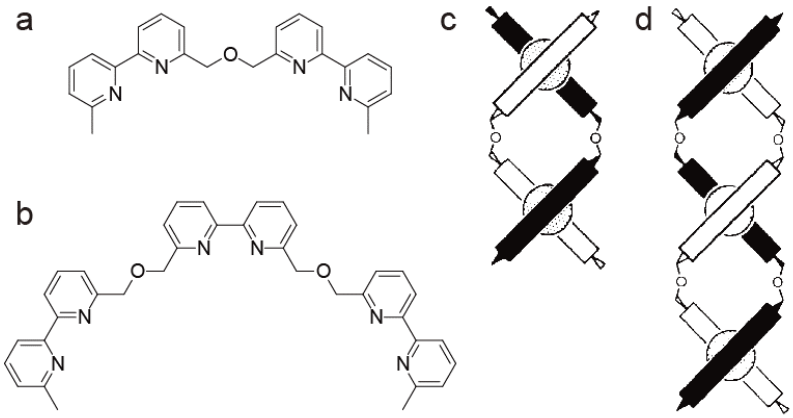


Figure 1-4. Chemical structure of oligobipyridine ligands, containing (a) two and (b) three 2,2′-bipyridine subunits separated by 2-oxapropylene bridges. (c, d) Schematic representation of the double-stranded helicates formed by complexation of two and three copper(I) cations, respectively, by the oligobipyridine ligands a and b.

Since J. -M. Lehn found the duble-stranded helicates, scientists focused on DNA helical structure. DNA is constructed from deoxyribose, phosphate, and bases by hydrogen bondings of set pair.[39-41] J. -M. Lehn reported a new area within the field of polymer chemistry by creating a polymer in which the monomeric units were held together by hydrogen bonds.[42] Inspired by this work, E. W. Meijer et al. focused on hydrogen bonding and created a supramolecular polymer based on the ureido-prymidinone motif. Their group reported that units of 2-ureido-4pyrimidone that dimerize strongly in a self-complementary array of four cooperative hydrogen bonds were used as the associating end group in reversible self-assembling polymer systems. These polymer networks with thermodynamically controlled architectures can be formed and their bond strength showed many properties, such as viscosity, chain length and so on.[43-44]

1-4. Supramolecular materials through non-covalent bond

Recently, many scientists have prepared supramolecular materials, which were formed by non-covalent bonds, for creating new soft machines and functional polymers. In soft machines, scientists use hydrogels, which are materials formed from the combination of solid and liquid components,have applications in surgery and drug delivery Generally, many biological gel composites are quite strong and tough. Thus, hydrogels prepared by using non-covalent bonds are used in creating bio-mimicry materials.[45-46]

R. Yoshida et al. created the self-oscillating gel which autonomously swells and de-swells periodically in a closed homogeneous solution without any external stimuli, similar to autonomic phenomena in life such as heartbeat. The self-oscillating gel was prepared by copolymerization of *N*-isopropylacrylamide (IPAAm) with ruthenium(II) tris-(2,2′-bipyridine) ($Ru(bpy)_3^{2+}$), a catalyst for the Belousov-Zhabotinsky (BZ) reaction. This gel exhibited swelling and de-swelling at the oxidized and reduced states of $Ru(bpy)_3$, respectively, and they also successfully created the self-walking gel.[47-52]

J. P. Gong et al. reported that polyampholytes, polymers bearing randomly dispersed cationic and anionic repeat groups, formed tough and viscoelastic hydrogels with multiple mechanical properties. These hydrogels were constructed from ionic bonds and they exhibited a wide distribution of strength. The strong bonds served as permanent crosslinks, imparting elasticity, whereas the weak bonds reversibly break and re-form, dissipating energy.[53]

Z. Bao et al. created a composite material composed of a supramolecular organic polymer with embedded nickel nanostructured microparticles, which showed mechanical and electrical self-healing properties at ambient conditions. Additionally, these materials were pressure- and flexion-sensitive and suitable for electronic skin applications.[54]

1-5. Supramolecular polymer based on cyclodextrin derivatives

CDs are famous host molecules in the field of supramolecular chemistry. A. Harada et al.[55-57] reported polyrotaxanes in which many CDs were entrapped onto a polymer chain by capping with bulky stopper groups at both ends of the polymer chain (Figure 1-5a). Additionally, they successfully created molecular tube: some α-CDs in the CD polyrotaxane were bonded by epichlorohydrin (Figure 1-5b).

K. Hirotsu, K. Fujita and I. Tabushi et al. reported the first direct evidence of the supramolecular polymer of 6-*O*-(*tert*-butyltio)-β-CD determined by single-crystal X-ray diffraction.[58] Since then, many crystal structures of 6-monosubstituted β-CDs with aliphatic [59-63] and aromatic [64-68] molecules has been reported.

A. Harada et al. reported supramolecular polymers consisting of modified CDs.[69-72] They investigated the formation of cyclodextrin-based supramolecular polymers, chiral supramolecular polymers and supramolecular [2]rotaxane polymers characterized by ^{1}H NMR, TOF MS, STM and so on (Figure 1-5c, d and e).

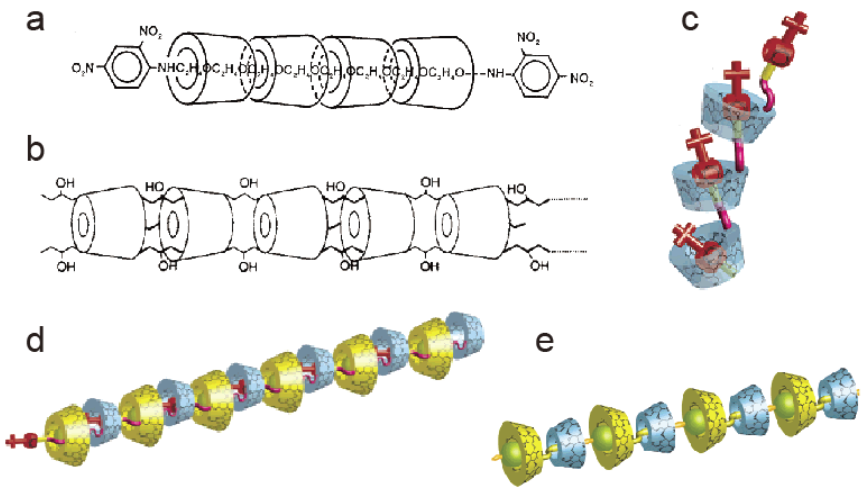


Figure 1-5. Chemical structure of (a) polyrotaxane (molecular necklace) and (b) molecular tube. (c, d and e) Schematic illustration of supramolecular linear polymer using modified CDs.

1-6. Stimuli-responsive supramolecular materials based on cyclodextrins

Supramolecular hydrogels are formed by mixing an aqueous solution of a CD polymer and that of a guest polymer. I. Tomatsu and A. Harada et al. created supramolecular hydrogels by mixing dodecyl-modified poly(acrylic acid) and water (Figure 1-6a). The supramolecular hydrogels showed gel-to-sol and sol-to-gel transitions in the presence and absence of α-CD respectively. They successfully created stimuli-responsive hydrogel systems using the interaction of CDs with polymer side chains.[73] Later, the authors reported photoresponsive supramolecular hydrogel utilizing molecular recognition of α-CD on the polymer side chains. Photoresponsive hydrogel, was prepared by mixing the aqueous solution of α-CD- and dodecyl-modified poly(acrylic acid)s at room temperature. The supramolecular hydrogels formed by molecular recognition between azobenzene (Azo) and α-CD units exhibited photresponsive sol-gel transitions (Figure 1-6b).[74] S. Tamesue and A. Harada et al.[75-76] also designed photoswitchable supramolecular sol-gel system by mixing curdlan modified α-CD as a host polymer and azobenzene modified poly(acrylic acid) as a guest polymer (Figure 1-6c). The morphology of the supramolecular hydrogels can be switched by photoirradiation with appropriate wavelength to control the formation of an inclusion complex, meaning that the connection or disconnection between the two polymers can be controlled by light.

Phase transition from sol to gel, reversibly, of the hydrogel containing β-CD and ferrocene monomer was also achieved by M. Nakahata and A. Harada et al. (Figure 1-6d). The supramolecular hydrogel exhibited redox-controlled self-healing properties[77].

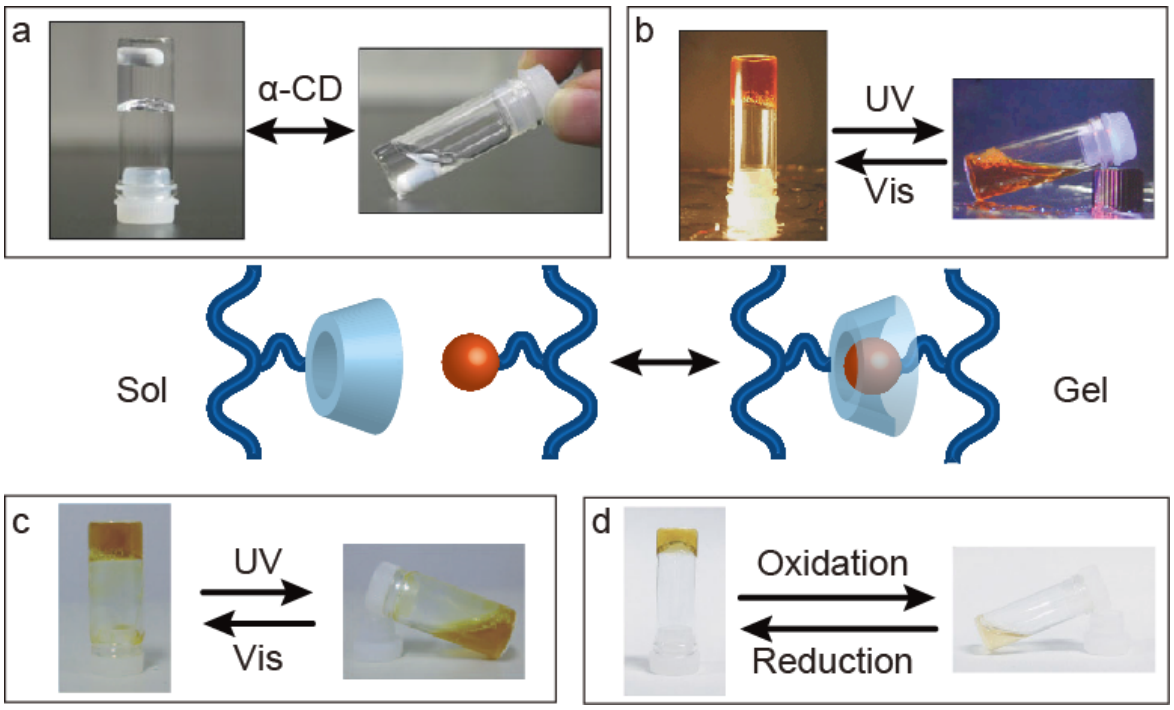


Figure 1-6. Stimuli responsive sol-gel phase transition of the CD modified polymer and the guest modified polymer controlled by chemical stimulus system using α-CD (a), chemical and photo stimuli system using azobenzene (b), photo stimuli system using azobenzene (c), and redox stimuli system using ferrocene (d).

1-7. Macroscopic self-assembly

A. Harada et al. developed macroscopic self-assembly through molecular recognition, which allows ones to visibly observe the molecular interaction (Figure 1-7). Pieces of host and guest gels, which are chemically crosslinked acrylamide-based gels with either CDs or small hydrocarbon-group guest moieties, adhere to one another via mutual molecular recognition of CDs and hydrocarbon groups on their surfaces.[78-79] In particular, gels modified α-CD and β-CD can selectively assemble with gels possessing *n*-butyl and *t*-butyl groups, respectively. This is because such assembly is driven by the formation of inclusion complexes between CD and guest group; the affinity of α-CD/*n*-butyl is higher than β-CD/*n*-butyl and the affinity of β-CD/*t*-butyl is higher than β-CD/*n*-butyl. Since creating this system, the external stimuli, such as light,[80] chemical,[81] temperature[82], and pH stimuli,[83] make it relatively easy to reversibly control adhesion and cleavage between hydrogel pieces in the macroscopic self-assembly system through host-guest interactions. For example, polyacrylamide-based hydrogels functionalized with Azo (guest) or cyclodextrin (host) moieties developed a photoregulated gel assembly system. Reversible adhesion and dissociation of the host gel from the guest gel can be controlled by photoirradiation. The differential affinities of α-CD or β-CD for the *trans*- Azo and *cis*- Azo are employed in the construction of a photoswitchable gel assembly system.[80]

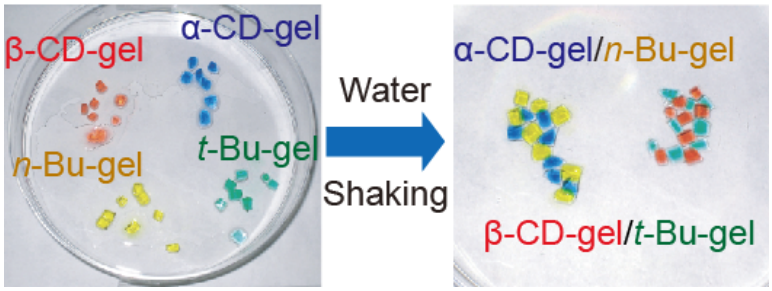


Figure 1-7. Host gels (α-CD-gel, blue; β-CD-gel, red) and guest gels (*n*-Bu-gel, yellow; *t*-Bu-gel, dark green) were placed in a petri dish. Adding water and shaking for a few minutes led to the selective formation of alternating self-assemblies.

1-8. Self-healing

1-8-1. Self-healing in biological systems

In biological systems, the healing response automatically (self-healing) begins when the region is injured by external forces. As the blood components spill into the site of injury, the platelets come into contact with exposed collagen and other elements of the extracellular matrix.[84] After jointing, the injured region was healed by metabolizing to new extracellular matrix and collagen, respectively. This self-healing taken by metabolizing was observed in the muscle fiber and vegetable leaflets. In the muscle fiber, dysferin-mediated membranes repaired at the damage place when the protease activated by calcium broke the protein in cells.[85-87]

1-8-2. Self-repairing materials composited repairing agent

Self-healing process inspired by biological systems needs to automatically repair damage without initiating an autonomous healing process. Such materials should respond autonomously to damage, and should possess capability to restore the un-damaged material's properties.

C. Dry et al.[88-94] reported the concrete materials composited polypropylene pipes implanted methylmethacrylate in hollow of pipes exhibited self-healing behavior after cracking itself. Moreover, they described the self-healing polymer which is similar to pipes repaired damage. An investigation polymer matrix composites was developed) which have the ability to self-repair after being triggered by cracking. It focused on the cracking of hollow repair fibers dispersed in a matrix and the subsequent timed release of repair chemicals, resulting in the sealing of matrix cracks, the restoration of strength in damaged areas and the ability to retard crack propagation. As a results, the healing system restores strength and retards crack growth against impact fracture and bend.

S. R. White et al.[95-107] have achieved autonomous mending of cracks by embedding

an appropriate catalyst and micro-capsules of monomer healing agent throughout polymer matrix (Figure 1-8). An embedded catalyst triggered polymerization of the healing agent to bond the crack faces. Their fracture experiments yield as much as 75% recovery in toughness.

I. P. Bond et al.[108-109] have introduced a novel fiber implanted fluorescent substance reinforced plastics which utilized a bleeding mechanism to achieve self-repairing visualization of damage.

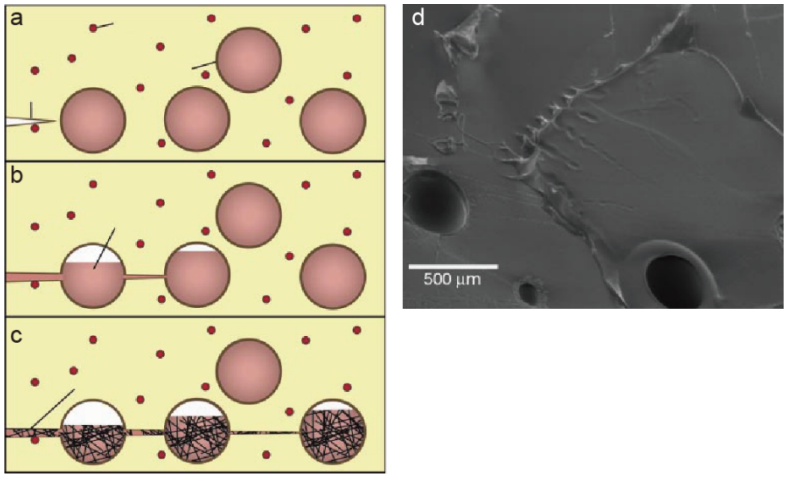


Figure 1-8. The autonomic healing concept by S. R. White et al. (a) Cracks form in the matrix wherever damage occurs. (b) The crack ruptures the microcapsules, releasing the healing agent into the crack plane through capillary action. (c) The healing agent contacts the catalyst, triggering polymerization that bonds the crack faces closed. (d) The repairing interface.

1-8-3. Self-healing materials using covalent bond

The concept of the self-healing by reversible covalent network is versatile Diels-Alder cycloaddition reactions (DA) and retro-DA (rDA) (Figure 1-9a).[110-112] F. Wudl et al. developed a self-healing concept using the thermally reversible DA/rDA reaction between star-shaped trivalent maleimides and tetravalent furans.[113-118] The damage event will break the DA-crosslinking points to form terminal maleimide and furan species, which in turn are able to react preferentially in a DA reaction, resulting in an average mending efficiency of about 50%. In 1979, H. Grigoras et al.[119] reported the synthesis of anthracene-methacrylic acid adducts, and their subsequent DA-Polymerization either thermally or Lewis acid ($TiCl_4$) induced.[120-121] N. Yoshie et al. reported a semicrystalline cross-linked polymer prepared by polymerization of furyl-telechelic poly(1,4-butylene succinate-*co*-1,3-propylene succinate) prepolymer ($PBPSF_2$) with tris-maleimide linker in bulk state. These materials change mechanical properties by two dynamic processes of melt-recrystallization and depolymerization-repolymerization and exhibited self-healable behavior.[122-129]

Disulfide bridges (S-S) are well-known as one of the reversible covalent bonds (Figure 1-9b).[130-131] B. Klumperman et al.[132] came up with a self-healing materials that is based on the use of disulfide links incorporated in a rubber network, which is able to fully restore its mechanical properties at moderate temperature. This result has been achieved by introducing disulfide groups in the network that are able to exchange, leading to renewal of cross-links across the damaged surfaces.

A. Takahara et al. and C. Yuan et al. reported the use of alkoxyamines as a reversible crosslinker for poly(methacrylic esters).[133-134] This type of linker is called dynamic covalent bond (Figure 1-9c). H. Otsuka et al.[135] developed a dynamic materials that had the ability to self-heal under mild conditions, such as under air at r. t., using a dynamic covalent bond unit, diarylbibenzofuranone, which is a dimer of arylbenzofuranone, a known antioxidant.

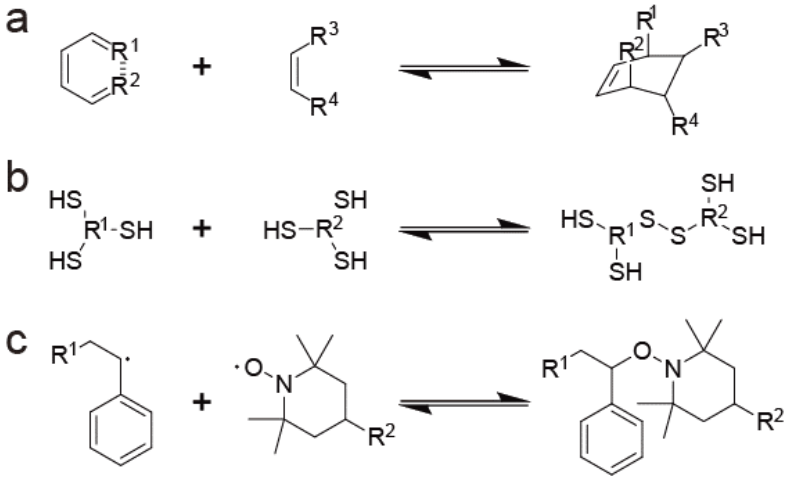


Figure 1-9. Chemical structure of (a) the Diels-Alder cycloaddition reactions, (b) the Thiol/disulfide linkages and (c) the Radical-based reactions.

1-8-4. Self-healing materials using non-covalent bond

There are four types of self-healing materials which were formed by (1) hydrogen bonds, (2) ionic interactions, (3) metal-ligands interactions and (4) π-π interactions (Figure 1-10). L. Leibler et al. synthesized a self-healable and shape-recovery thermoreversible rubber which was formed by multivalent fatty acids and urea with three different type of hydrogen bonding motifs, diamido tetraethyl triurea, di(amido ethyl) urea, and amidoethyl imidazolidone. The author described this material can be easily processed, re-used and recycled.[136-140]

T. Aida et al. and C. J. Hawker et al. reported aqua materials which was formed by mixing clay and a dendritic molecular binder through ionic interactions. This material can be molded into shape-persistent, free-standing objects owing to its exceptionally great mechanical strength, and rapidly and completely self-heals when damaged. The author contributed that this material is formed only by non-covalent forces resulting from the specific design of a telechelic dendritic macromolecule with multiple adhesive termini for binding to clay.[141-143]

Additionally, materials, which achieved self-healing abilities through metal-ligand interactions, were reported by S. J. Rowan et al.[144], N. Holten-Andersen et al.[145], P. B. Messersmith et al.[146], H. Birkedal et al.[147], and M. D. Hager and U. S. Schubert et al.[148]. S. J. Rowan et al. reported the metallosupramolecular polymers, consisted of telechelic, rubbery, low-molecular-mass polymers with ligand end groups that are non-covalently linked through metal-ion binding, can be mended through exposure to light.

Self-healing materials based on aromatic π-π stacking and interactions were first reported by Burattini et al. They prepared supramolecular materials from a low molecular weight polydiimide which contains multiple π-electron-poor receptor site along its backbone. The polydiimide forms homogeneous films with a siloxane polymer that features π-electron-rich pyrenyl end-groups. As a result, these materials exhibited rapid and reversible complexation behavior in solution and healable characteristics in the solid state in response to temperature. The authors described π-π stacking interactions drive formation of a new network and so lead to good damage-recovery characteristics of the two-component blend.[149-152]

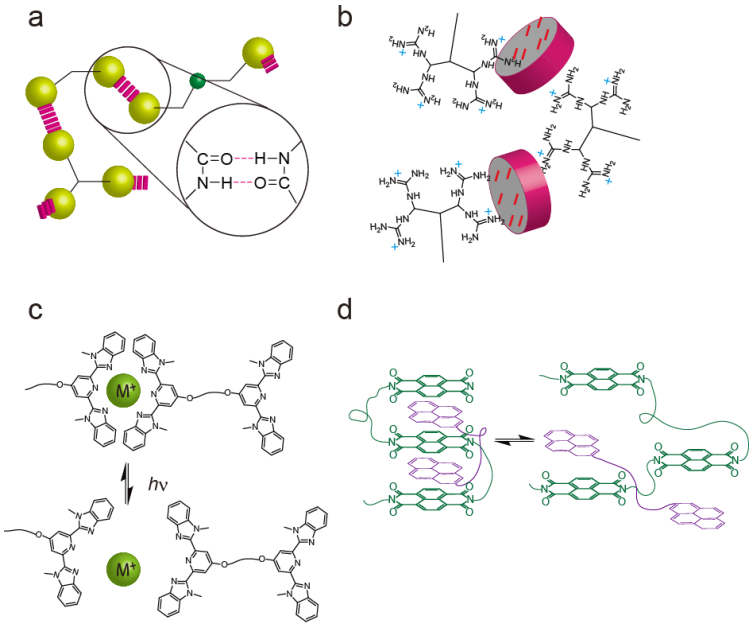
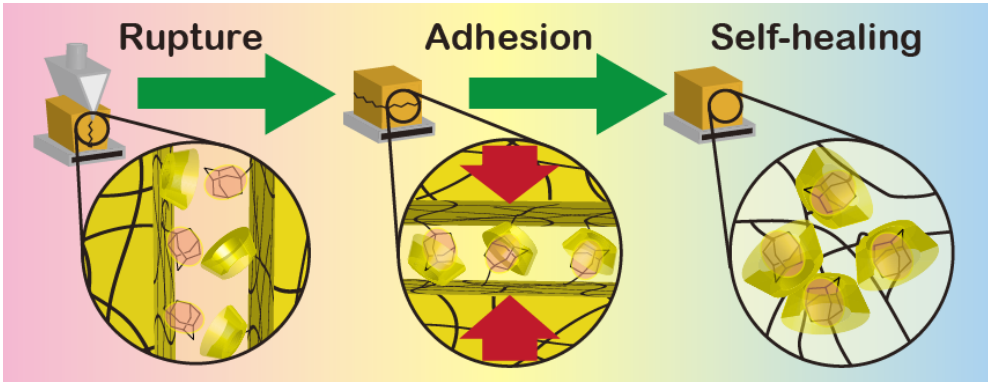


Figure 1-10. Four types of non-covalent bonds, (a) hydrogen bonds, (b) ionic interaction, (c) metal-ligand interaction and (d) π-π interaction, for creating self-healing materials.

1-9. Scope and outline of this thesis

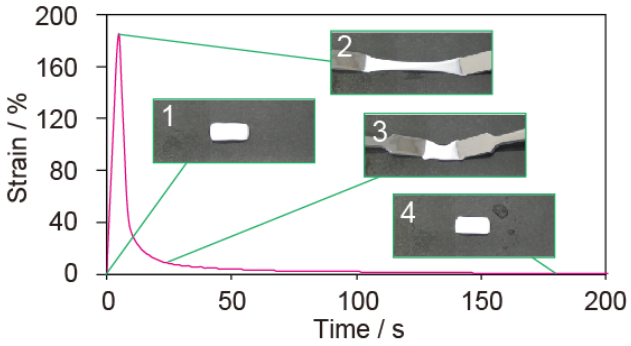
The present thesis focuses on the self-healing properties of materials which was cross-linked by inclusion complexes between cyclodextrin and alkyl guest groups. Since the CD has molecular recognition, the supramolecular material composed by inclusion complexes of CD was expected to show the self-healing properties such as biological systems. Additionally, the author also focuses on mechanical properties of the self-healing materials.

In *Chapter 2*, radical copolymerization of acrylamide, CD modified acrylamide, and guest monomers (*n*-butyl acrylate or adamantane acrylamide) in aqueous solutions yield self-standing and self-healable supramolecular hydrogels (CD-guest gels). The self-healing properties of the cuboid-shaped CD-guest gels are determined by rejoining experiments. After standing for 24 hours, the cut gel pieces sufficiently heal to form a single gel, and the initial strength is restored. Adhesive mechanism was determined by competitive experiments. The stress healing ratio of the CD-guest gels which evaluated by rupture experiments increase with increasing healing time.



In *Chapter 3*, the supramolecular hydrogel was prepared by polymerization of the inclusion complexes between β-cyclodextrin acrylamide and adamantane acrylamide monomers. The β-cyclodextrin-adamantane gel (βCD-Ad gel) shows high stretching property and shape recovery. The mechanical properties of the βCD-Ad gel was evaluated

by tensile experiments. The βCD-Ad gel showed high stretching from initial state (990%). The different competitive molecules (α-CD, β-CD, γ-CD and 1-adamantane carboxylic acid sodium salt (AdCANa)) were added to the βCD-Ad gel; the breaking stress of the βCD-Ad material decrease significantly when β-CD and AdCANa were used. Properties of shape recovery was determined by creep experiments of the βCD-Ad gel and control sample (acrylamide gel cross-linked by methylenebis(acrylamide)).



In *Chapter 4*, the adhesion between semi-hard materials containing cyclodextrin or adamantane were investigated by tensile strength of adhesive materials. The adhesive behavior on the adhesive interface was evaluated by optical microscope observation. Hard materials containing cyclodextrin and adamantane (CD-Ad P) were prepared for creating self-healing hard materials. The self-healing behavior of βCD-Ad P was determined by optical microscope observation. Additionally, The βCD-Ad P showed high stress recovery ratio of initial strength by rupture experiments.

In *Chapter 5*, hydrogels crosslinked between cyclodextrin polymers with star-shaped tetravalent guest polymer were prepared by radical copolymerization of acrylamide-βCD with star-shaped tetravalent poly(ethyleneglycol) (tetra-PEG) with adamantane at the end (TPAd). The obtained hydrogels, CD-TPAd gels, showed self-healing ability, which was evaluated by tensile experiments.

References

1. Lehn, J. -M. *Pure Appl. Chem.* **1978**, *50*, 871.
2. Lehn, J. -M. *Acc. Chem. Res.* **1978**, *11*, 49.
3. Lehn, J. -M. *Supramolecular chemistry*: *Concepts and Perspectives*; VCH: New York, **1995**.
4. Lehn, J. -M. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4763.
5. Pressman, B. C. *Annu. Rev. Biochem.* **1976**, *45*, 501.
6. Pressman, B. C.; Harris, E. J.; Jagger, W. S.; Johnson, J. H.; *Proc. Natl. Acad. Sci. USA* **1967**, *58*, 1949.
7. Fischer, E. *Ber. Deutsch. Chem. Ges*. **1894**, *27*, 2985.
8. Cannon, W. R.; Singleton, S. F.; Benkovic, S. J. *Nat. Struct. Biol.* **1996**, *3*, 821.
9. Scheneider, H. -J. *Angew. Chem. Int. Ed.* **2009**, *48*, 3924.
10. Schneider, H. -J.; Blatter, T.; Eliseev, A.; Rudiger, V.; Raevsky, O. A. *Pure Appl. Chem.* **1993**, *65*, 2329.
11. Gokel, G. M. *Crown Ether*; Royal Society of Chemistry: Cambridge, **1990**.
12. Witkop, B. *Science* **1968**, *162*, 318.
13. De Greef, T. F. A.; Smulders, M. M. J.; Wolffs, M.; Schenning, A. P. H. J.; Silibesma, R. P.; Meijer, E. W. *Chem.Rev.* **2009**, *109*, 5687.
14. Ma, J. C.; Dougherty, D. A. *Chem. Rev.* **1997**, *97*, 1303.
15. Hunter, C. A.; Snders, J. K. M. *J. Am. Chem. Soc.* **1990**, *112*, 5525.
16. Smithrud, D. B.; Sanford, E. M.; Chao, I.; Ferguson, S. B.; Carcanague, D. R.; Evanseck, J. D.; Houk, K. N.; Diederich, F. *Pure Appl. Chem.* **1990**, *62*, 2227.
17. Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 7017.
18. Pedersen, C. J. *Angew. Chem.* **1988**, *100*, 1053; *Angew. Chem. Int. Ed. Engl.* **1988**, *27*, 1053.
19. Dietrich, B.; Lehn, J. -M.; Sauvage, J. -P. *Tetrahedron* **1973**, *29*, 1629.
20. Lehn, J. -M. *Struct. Bonding*; Springer: New York, **1973**.
21. Bender, M. L.; Komiyama, M. *Cyclodextrin Chemistry*; Springer: Berlin, **1978**.
22. Szejtli, J. *Cyclodextrin Technology*; Kluwer: Dordrecht, **1988**.
23. Gutsuche, C. D. *Acc. Chem. Res.* **1983**, *65*, 387.
24. vanDienst, E.; Bakker, W. I. I.; Engbersen, J. F. J.; Verboom, W.; Reinhoudt, D. N. *Pure Apply. Chem.* **1993**, *65*, 387.
25. Shinkai, S. *Terrahedron* **1993**, *49*, 8933.
26. Ogoshi, T.; Yamagishi, T. *Bull. Chem. Soc. Jpn.* **2013**, *86*, 312.
27. Ogoshi, T.; Yamagishi, T. *Eur. J. Org. Chem.* **2013**, 2961.
28. Diederich, F. *Angew. Chem. Int. Ed.* **1988**, *27*, 362.
29. Davis, A. P. *Chem. Soc. Rev.* **1993**, *22*, 243.
30. Lehn, J. -M. *Struct. Bonding*; Springer: New York, **1973**.
31. Connors, K. A. *Chem. Rev.* **1997**, *97*, 1325.
32. Szejtli, J. *Chem. Rev.* **1998**, *98*, 1743.
33. Pringsheim, H. *Chemistry of Saccharides*; McGraw Hill: New York, **1932**.
34. Cram, D. J.; Cram, J. M. *Science* **1974**, *50*, 871.
35. Lehn, J.-M.; Rigault, A.; Siegel, J.; Harrowfield, J.; Chevrier, B.; Moras, D. *Proc. Natl. Acad. Sci. USA* **1987**, *84*, 2565.
36. Lehn, J.-M. *Angew. Chem. Int. Ed.* **1988**, *27*, 89.
37. Komiyama, M.; Breaux, E. J.; Bender, M. L. *Bioorg. Chem.* **1977**, *6*, 127.
38. Breslow, R.; Doherty, J. B.; Guillot, G.; Lipsey, C. *J. Am. Chem. Soc.* **1978**, *100*, 3227.
39. Watson, J. D.; Crick, F. H. C. *Nature* **1953**, *171*, 747.

40. Stadler, R.; de Lucca Freitas, L. *Colloid Polym. Sci.* **1986**, *264*, 773.
41. de Lucca Freitas, L.; Stadler, R. *Macromolecules* **1987**, *20*, 2478.
42. Fouquey, C.; Lehn, J. -M.; Levelut, A. -M. *Adv. Mater.* **1990**, *5*, 254.
43. Sijibesma, R. P.; Beijer, F. H.; Brunsveld, L.; Folmer, B. J. B.; Ky Hirschberg, J. H. K.; Lange, R. F. M.; Lowe, J. K. L.; Merijer, E. W. *Science* **1997**, *278*, 1601.
44. Brunsveld, L.; Folmer, B. J. B.; Meijer, E. W.; Sijbesma, R. P. *Chem. Rev.* **2001**, *101*, 4071.
45. Calvert, P. *Adv. Mater.* **2009**, *21*, 743.
46. Aida, T.; Meijer, E. W.; Stupp, S. I. *Science* **2012**, *335*, 813.
47. Yoshida, R.; Takahashi, T.; Yamaguchi, T.; Ichijo, H. *J. Am. Chem. Soc.* **1996**, *118*, 5134.
48. Yoshida, R.; Takahashi, T.; Yamaguchi, T.; Ichijo, H. *Adv. Mater.* **1997**, *9*, 175.
49. Maeda, S.; Hara, Y.; Sakai, T.; Yoshida, R.; Hashimoto, S. *Adv. Mater.* **2007**, *19*, 3480.
50. Yoshida, R. *Bull. Chem. Soc. Jpn* **2008**, *81*, 676.
51. Yoshida, R.; Sakai, T.; Hara, Y.; Maeda, S.; Hashimoto, S.; Suzuki, D.; Murase, Y. *J. Controlled Release* **2009**, *140*, 186.
52. Yoshida, R. *Adv. Mater.* **2010**, *22*, 3463.
53. Sun, T. L.; Kurokawa, T.; Kuroda, S.; Ihsan, A. B.; Akasaki, T.; Sato, K.; Haque, Md. A.; Nakajima, T.; Gong, J. P. *Nat. Mater.* **2013**, *12*, 932.
54. Tee, B. C. -K.; Wang, C.; Allen, R.; Bao, Z. *Nat. Nanotechnol.* **2012**, *7*, 825.
55. Harada, A.; Li, J.; Kamachi, M. *Nature* **1992**, *356*, 325.
56. Harada, A.; Li, J.; Kamachi, M. *Nature* **1993**, *364*, 516.
57. Harada, A.; Li, J.; Kamachi, M. *Nature* **1994**, *370*, 126.
58. Hirotsu, K.; Higuchi, T.; Fujita, K.; Ueda, T.; Shinoda, A.; Imoto, T.; Tabushi, I. *J. Org. Chem.* **1982**, *47*, 1143.
59. Harata, K.; Rao, C. T.; Pitha, J.; Fukunaga, K.; Uekama, K. *Carbohydr. Res.* **1991**, *222*, 37.
60. Di Blasion, B.; Pavone, V.; Nastri, F.; Isernia, C.; Saviano, M.; Pedone, C.; Cucinotta, V.; Impellizzeri, G.; Rizzarelli, E.; Vecchio, G. *Proc. Natl. Acad. Sci. U. S. A.* **1992**, *89*, 7218.
61. Hanessian, S.; Benalil, A.; Simard, M.; Bëlanger-Gariepy, F. *Terahedron* **1995**, *51*, 10149.
62. Mentzafos, D.; Terzis, A.; Coleman, A. W.; de Rango, C. *Carbohydr. Res.*, **1996**, *282*, 125.
63. Harata, K.; Takenaka, Y.; Yoshida, N. *J. Chem. Soc., Perkin Trans. 2* **2001**, *9*, 1667.
64. Kamitori, S.; Hirotsu, K.; Higuchi, T.; Fujita, K.; Yamamura, H.; Imoto, T.; Tabushi, I. *J. Chem. Soc., Perkin Trans. 2* **1987**, *1*, 7.
65. Liu, Y.; You, C. -C.; Zhang, M.; Weng, L. -H.; Wada, T.; Inoue, Y. *Org. Lett.* **2000**, *2*, 2761.
66. Liu, Y.; Fan, Z.; Zhang, H. -Y.; Diao, C. -H. *Org. Lett.* **2003**, *5*, 251.
67. Liu, Y.; Fan, Z.; Zhang, H. -Y.; Yang, Y. -M.; Ding, F.; Liu, S. -X.; Wu, X.; Wada, T.; Inoue, Y. *J. Org. Chem.* **2003**, *68*, 8345.
68. Eliadou, K.; Giastas, P.; Yannakopoulou, K.; Mavridis, I. M. *J. Org. Chem.* **2003**, *68*, 8550.
69. Miyauchi, M.; Harada, A. *J. Am. Chem. Soc.* **2004**, *126*, 11418.
70. Miyauchi, M.; Hoshino, T.; Yamaguchi, H.; Kamitori, S.; Harada, A. *J. Am. Chem. Soc.* **2005**, *127*, 2034.
71. Miyauchi, M.; Takashima, Y.; Yamaguchi, H.; Harada, A. *J. Am. Chem. Soc.*

2005, *127*, 2984.
72. Tomimasu, N.; Kanaya, A.; Takashima, Y.; Yamaguchi, H.; Harada, A. *J. Am. Chem. Soc.* **2009**, *131*, 12339.
73. Tomatsu, I.;Hashidzume, A.; Harada, A. *Macromol. Rapid Commun.* **2005**, *26*, 825.
74. Tomatsu, I.; Hashidzume, A.; Harada, A. *Macromolecules* **2005**, *38*, 5223.
75. Tamesue, S.; Takashima, Y.; Yamaguchi, H.; Shinkai, S.; Harada, A. *Angew. Chem. Int. Ed.* **2010**, *49*, 7461.
76. Tamesue, S.; Takasima, Y.; Yamaguchi, H.; Sinkai, S.; Harada, A. *Eur. J. Org. Chem.* **2011**, 2801.
77. Nakahata, M.; Takashima, Y.; Yamaguchi H.; Harada, A. *Nat. Commun.* **2011**, *2*, 511.
78. Harada, A.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Yamaguchi, H. *Nat. Chem.* **2011**, *3*, 34.
79. Yamaguchi, H.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Harada, A. *Macromolecules* **2011**, *44*, 2395.
80. Yamaguchi, H.; Kobayashi, Y.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Harada, A. *Nat. Commun.* **2012**, *3*, 603.
81. Zheng, Y.; Hashidzume, A.; Takashima, Y.; Yamaguchi, H.; Harada, A. *Nat. Commun.* **2012**, *3*, 831.
82. Zheng, Y.; Hashidzume, A.; Takashima, Y.; Yamaguchi, H.; Harada, A. *ACS Macro Lett.* **2012**, *1*, 1083.
83. Zheng, Y.; Hashidzume, A.; Harada, A. *Macromol. Rapid Commun.* **2013**, *34*, 1062.
84. Diegelmann, R. F.; Evans, M. *front. biosci.* **2004**, *9*, 283.
85. Han, R.; Campbell, K. P. *Curr. Opin. Cell Biol.* **2007**, *19*, 409.
86. McNeil, A. K.; Rescher, U.; Gerke, V.; McNeil, P. L. *J. Biol. Chem.* **2006**, *281*, 35202.
87. Han, R.; Bansal, D.; Miyake, K.; Muniz, V. P.; Weiss, R. M.; McNeil, P. L.; Campbell, K. P.; *J. Clin. Invest.* **2007**, *117*, 1805.
88. Dry, C.; Corsaw, M. *Cem. Concr. Res.* **2003**, *33*, 1723.
89. Dry, C. *Smart Mater. Struct.* **1994**, *3*, 118.
90. Dry, C.; Mcmillan, W. *Smart Mater. Struct.* **1996**, *5*, 297.
91. Dry, C. *Compos. Struct.* **1996**, *35*, 263.
92. Dry, C.; Mcmillan, W. *Smart Mater. Struct.* **1997**, *6*, 35.
93. Dry, C. *Cem. Concr. Res.* **2000**, *30*, 1969.
94. Li, V. C.; Lim, Y. M.; Chan, Y. W. *Composites, Part B* **1998**, *29B*, 819.
95. White, S. R.; Sottos, N. R.; Geubelle, P. H.; Moore, J. S.; Kessler, M. R.; Sriram, S. R.; Brown, E. N.; Viswanathan, S. *Nature* **2001**, *409*, 794.
96. Rule, J. D.; Moore, J. S. *Macromolecules* **2002**, *35*, 7878.
97. Brown, E. N.; Kessler, M. R.; Sottos, N. R.; White, S. R. *J. Microencapsulation* **2003**, *20*, 719.
98. Brown, E. N.; White, S. R.; Sottos, N. R. *J. Mater. Sci.* **2004**, *39*, 1703.
99. Liu, X.; Lee, J. K.; Yoon, S. H.; Kessler, M. R. *J. Appl. Polym. Sci.* **2006**, *101*, 1266.
100. Maiti, S.; Shankar, C. P.; Geubelle, H.; Kieffer, J. *J. Eng. Mater. Technol.* **2006**, *128*, 595.
101. Cho, S. H.; Andersson, H. M.; White, S. R.; Sottos, N. R.; Braun, P. V. *Adv. Mater.* **2006**, *18*, 997.
102. Jones, A. S.; Rule, J. D.; Moore, J. S.; White, S. R.; Sottos, N. R. *Chem. Mater.*

2006, *18*, 1312.
103. Keller, M. W.; White, S. R.; Sottos, N. R. *Adv. Funct. Mater.* **2007**, *17*, 2399.
104. Toohey, K. S.; Sottos, N. R.; Lewis, J. A.; Moore, J. S.; White, S. R. *Nat. Mater.* **2007**, *6*, 581.
105. Hansen, C. J.; Wu, W.; Toohey, K. S.; Sottos, N. R.; White, S. R.; Lewis, J. A. *Adv. Mater.* **2009**, *21*, 4143.
106. McIlroy, D. A.; Blaiszik, B. J.; Caruso, M. M.; White, S. R.; Moore, J. S.; Sottos, N. R. *Macromolecules* **2010**, *43*, 1855.
107. Jin, H.; Mangun, C. L.; Griffin, A. S.; Moore, J. S.; Sottos, N. R.; White, S. R. *Adv. Mater.* **2014**, *26*, 282.
108. Pang, J. W. C.; Jody, W. C.; Bond, I. P. *Compos. Sci. Technol.* **2005**, *65*, 1791.
109. Pang, J. W. C.; Bond, I. P. *Composites, Part A* **2005**, *36*, 183.
110. Chujo, Y.; Sada, K.; Saegusa, T. *Macromolecules* **1990**, *23*, 2636.
111. Yang, Y.; Urban, M. W. *Chem. Soc. Rev.* **2013**, *42*, 7446.
112. Bergman, S. D.; Wudl, F. *J. Mater. Chem.* **2008**, *18*, 41.
113. Chen, X.; Wudl, F.; Mal, A. K.; Shen, H.; Nutt, S. R. *Macromolecles* **2003**, *36*, 1802.
114. Chen, X.; Dam, M. A.; Ono, K.; Mal, A.; Shen, H.; Nutt, S. R.; Sheran, K.; Wudl, F. *Science* **2002**, *295*, 1698.
115. Murphy, E. B.; Ed Bolanos; Schaffner-Hamann, C.; Wudl, F.; Nutt, S. R.; Auad, M. L. *Macromolecules* **2008**, *41*, 5203.
116. Canary, S. A.; Stevens, M. P. *J. Polym. Sci. Part A Polym. Chem.* **1992**, *30*, 1755.
117. Inglis, A. J.; Nebhani, L.; Altintas, O.; Schmidt, F. G.; Barner-Kowollik, C. *Macromolecules* **2010**, *43*, 5515.
118. Reutenauer, P.; Buhler, E.; Boul, P. J.; Candau, S. J.; Lehn, J. -M. *Chem. Eur. J.* **2009**, *15*, 1893.
119. Dumitrescu, S.; Grigoras, M.; Natansohn, A. *J. Polym. Sci. Polym. Lett. Ed.* **1979**, *17*, 553.
120. Wiggins, K. M.; Syrett, J. A.; Haddleton, D. M.; Bielawski, C. W. *J. Am. Chem. Soc.* **2011**, *133*, 7180.
121. Jones, J. R.; Liotta, C. L.; Collard, D. M.; Schiraldi, D. A. *Macromoleculs* **1999**, *32*, 5786.
122. Watanabe, M.; Yoshie, N. *Polymer* **2006**, *47*, 4946.
123. Ishida, K.; Yoshie, N. *Macromolecules* **2008**, *41*, 4753.
124. Ishida, K.; Yoshie, N. *Macromol. Biosci.* **2008**, *8*, 916.
125. Yoshie, N.; Watanabe, M.; Araki, H.; Ishida, K. *Polymer Degradation and Stability* **2010**, *95*, 826.
126. Ishida, K.; Nishiyama, Y.; Michimura, Y.; Oya, N.; Yoshie, N. *Macromolecules* **2010**, *43*, 1011.
127. Ishida, K.; Weibel, V.; Yoshie, N. *Polymer* **2011**, *52*, 2877.
128. Yoshie, N.; Saito, S.; Oya, N. *Polymer* **2011**, *52*, 6074.
129. Oya, N.; Saito, S.; Furuhashi, Y.; Yoshie, N. *J. Polym. Sci. Part A Polym. Chem.* **2012**, *50*, 1926.
130. Chujo, Y.; Sada, K.; Naka, A.; Nomura, R.; Saegusa, T. *Macromolecules* **1993**, *26*, 883.
131. Tsarevsky, N. V.; Matyjaszewski, K. *Macromolecules* **2002**, *35*, 9009.
132. Canadell, J.; Goossens, H.; Klumperman, B. *Macromolecules* **2011**, *44*, 2536.
133. Higaki, Y.; Otsuka, H.; Takahara, A. *Macromolecules* **2006**, *39*, 2121.
134. Yuan, C.; Rong, M. Z.; Zhang, M. Q.; Zhang, Z. P.; Yuan, Y. C. *Chem. Mater.* **2011**, *23*, 5076.

135. Imato, K.; Nishihara, M.; Kanehara, T.; Amamoto, Y.; Takahara, A.; Otsuka, H. *Angew. Chem. Int. Ed.* **2012**, *51*, 1138.
136. Cordier, P.; Tournilhac, F.; Soulie-Ziakovic, C.; Leibler, L. *Nature* **2008**, *451*, 7925.
137. Montarnal, D.; Cordier, P.; Soulie-Ziakovic, C.; Tournilhac, F.; Leibler, L. *J. Polym. Sci. Part A Polym. Chem.* **2008**, *46*, 977.
138. Montarnal, D.; Tournilhac, F.; Hidalgo, M.; Counturier, J.-L.; Leibler, L. *J. Am. Chem. Soc.* **2009**, *131*, 7966.
139. Tournilhac, F.; Cordier, P.; Montarnal, D.; Soulie-Ziakovic, C.; Leibler, L. *Macromol. Symp.* **2010**, *291*, 84.
140. Maes, F.; Montarnal, D.; Cantournet, S.; Tournilhac, F.; Corte, L.; Leibler, L. *Soft Matter* **2012**, *8*, 1681.
141. Wang, Q.; Mynar, J. L.; Yoshida, M.; Lee, E.; Lee, M.; Okuro, K.; Kinbara, K.; Aida, T. *Nature* **2009**, *463*, 339.
142. Hunt, J. N.; Feldman, K. E.; Lynd, N. A.; Deek, J.; Campos, L. M.; Spruell, J. M.; Hernandez, B. M.; Kramer, E. J.; Hawker, C. J. *Adv. Mater.* **2011**, *23*, 2327.
143. Tamesue, S.; Ohtani, M.; Yamada, K.; Ishida, Y.; Spruell, J. M.; Lynd, N. A.; Hawker, C. J.; Aida, T. *J. Am. Chem. Soc.* **2013**, *135*, 15650.
144. Burnworkth, M.; Tang, L.; Kumpfer, J. R.; Duncan, A. J.; Beyer, F. L.; Fiore, G. L.; Rowan, S. J.; Weder, C. *Nature* **2011**, *472*, 334.
145. Holten-Anderson, N.; Harrison, M. J.; Brikedal, H.; Lee, B. P.; Messersmith, P. B.; Lee, K. Y.; Waite, J. H. *Proc. Natl. Acad. Sci. U. S. A.* **2011**, *108*, 2651.
146. He, L.; Fullenkamp, D. E.; Rivera, J. G.; Messersmith, P. B. *Chem. Commun.* **2011**, *47*, 7497.
147. Krogsgaard, M.; Behrens, M. A.; Pedersen, J. S.; Birkedal, H. *Biomacromolecules* **2013**, *14*, 297.
148. Bode, S.; Zedler, L.; Schacher, F. H.; Dietzek, B.; Schmit, M.; Popp, J.; Hager, M. D.; Schubert, U. S. *Adv. Mater.* **2013**, *25*, 1634.
149. Burattini, S.; Colquhoun, H. M.; Greenland, B. M.; Hayes, W.; *Faraday Discuss.* **2009**, *143*, 251.
150. Burattini, S.; Greenland, B. W.; Chappell, D.; Colquhoun, H. M.; Hayes, W. *Chem. Soc. Rev.* **2010**, *39*, 1973.
151. Burattini, S.; Greenland, B. W.; Merino, D. H.; Weng, W.; Seppala, J.; Colquhoun, H. M.; Hayes, W.; Mackay, M. E.; Hamley, I. W.; Rowan, S. J. *J. Am. Chem. Soc.* **2010**, *132*, 12051.
152. Burattini, S.; Greenland, B. W.; Hayes, W.; Mackay, M. E.; Rowan, S. J.; Colquhoun, M. *Chem. Mater.* **2011**, *23*, 6.

Chapter 2

Preorganized Hydrogel: Self-Healing Properties of Supramolecular Hydrogels Formed by Polymerization of Host–Guest-Monomers that Contain Cyclodextrins and Hydrophobic Guest Groups

2-1. Introduction

Self-healing and self-repairing materials [1-7] have attracted much attention due to an improvement in the life-time of materials. Recently, the development of self-healing materials has become a central issue in polymer chemistry. Conventional polymers have difficulty in self-healing because they do not reform covalent bonds and their cut-surfaces do not re-adhere unless specific groups are introduced into the polymeric materials. There are three methods to create self-healing materials, such as the storage of healing agents,[8-18] reversible covalent bond formation with external stimuli,[19-25] and the construction of healing materials by non-covalent bonds.[26-34] Healing agent storage methods effectively produce self-healing materials by using hollow fibers, particles, and microcapsules. Reversible covalent bond systems formed using the Diels–Alder reaction[19-25] and the interconversion between disulfide groups and thiols[35-37] have a healing ability for re-mendable polymers with external stimuli. More recently, dynamic equilibria between propagating radicals and dormant covalent species in controlled free-radical polymerizations have realized photoinduced self-healing of photoresponsive covalently crosslinked polymers.[38-39] One of the most efficient ways to produce autonomously self-healing materials is a non-covalently bonded system where the polymerization and/or the crosslinking occur by intermolecular

interactions of the monomer units and/or the side chains by using hydrogen bonds,[40] π–π stacking interactions,[41-43] certain metal–ligand coordination bonds,[44] or ion interactions.[45] The host–guest interaction would be an effective way of preparing self-healing materials. Self-healing materials formed by host–guest interactions should recover their initial strength even after being cut in half and subsequently rejoined. Previously, Harada et al. have reported supramolecular hydrogels possessing host or guest polymers with selective adhesion.[46,48-49] Pieces of host and guest gels, which are chemically crosslinked acrylamide-based gels with either cyclodextrins (CDs) or small hydrocarbon-group guest moieties, adhere to one another through the mutual molecular recognition of CDs and hydrocarbon groups on the surface of the gels.[48-49] On the other hand, supramolecular gels, which consist of host and guest polymers crosslinked by host − guest interactions, exhibit self-healing properties, which reach 84% of the initial gel's strength at the cut gel surfaces.[47] Ideally, the strength of self-healable supramolecular materials would be completely restored through host–guest interactions. The introduction of a large number of host and guest units into the polymer chain may realize complete recovery. To construct self-healable supramolecular materials with completely recoverable material strength, the author hypotheses that preorganization of the host and guest monomers improves the self-healing efficiency. Herein, the author employs the radical copolymerization of monomers of a complex of a CD host and aliphatic guest in aqueous solution. The polymerization of inclusion complexes forms non-covalent crosslinks between polymer chains to yield supramolecular hydrogels. When the gels are cut, cooperative host–guest complexation on the cut surfaces should effectively recover the material strength. The author prepared supramolecular hydrogels (CD–guest gels), which consist of poly(acrylamide) modified with CDs and aliphatic guest groups on a polymer chain.

2-2. Experimental Section

Materials. α-Cyclodextrin, β-cyclodextrin were obtained from Junsei Chemical Co., Ltd. Ammonium peroxodisulfate, [2-(dimethylamino)ethyl]dimethylamine, sodium hydrogen carbonate, and 1-aminoadamantan were obtained from Nacalai Tesque Inc. Acryloyl chloride and butyl acrylate were obtained from Tokyo Kasei Inc. DMSO-d_6 was obtained from Merck & Co., Inc. A highly porous synthetic resin (DIAION HP-20) used for column chromatography was purchased from Mitsubishi Chemical Co., Ltd. Water used for the preparation of the aqueous solutions (except for NMR measurements) was purified with a Millipore Elix 5 system. Other reagents were used without further purification.

Measurements. One dimensional NMR spectra were recorded with a JEOL ECA-500 NMR spectrometer at 30 ^{o}C. Chemical shifts were referenced to the solvent values (δ = 2.49 ppm for DMSO-d_6). Dynamic viscoelasticity were measured using an Anton Paar MCR301 rheometer at strain of 0.1%. Mechanical properties of the gel were measured by the rupture testing system (Creep meter, RE-33005B, Yamaden Ltd.). Gel permeation chromatography (GPC) was performed in formamide (0.30 mL/min) using an TOSOH GPC-8020 Model II equipped with TOSOH TSKgel α-M column to determine molecular weights (M_n). M_n value of host-guest gels were measured with respect to polystyrene sulfonate Na salt (PSSNa) standards (American polymer standards Corp., Mentor, Ohio).

Preparation of Monomers. α-Cyclodextrin and β-cyclodextrin host monomers (AAm-αCD and AAm-βCD) and *N*-adamantane-1-yl-acrylamide (AAm-Ad) were prepared by previously reported procedures with slight modification.[46]

Preparation of AAm-αCD. 6-Amino-α-CD (1.9 g, 2.0 mmol) was dissolved in 100 mL of $NaHCO_3$ aq. (840 mg) and pH of the solution was adjusted to around 10 with NaOH. Acryloyl chloride (350 μL, 3.9 mmol) was added to the solution of 6-amino-α-CD on ice bath. The solution was stirred for 4 hours on ice bath. After the prescribed time, the solution was evaporated to 40% of the total volume and poured into acetone (1 L). The precipitate was collected by centrifugation, and then dried with vacuum oven for an overnight. The crude product was purified by reversed phase chromatography using HP-20 polystyrene gel (methanol/water) to give acrylamide α-CD (780 mg, 41%). ^{1}H NMR (500 MHz, DMSO-d_6): δ 7.99 (t, 1H, amide), 6.26 (dd, 1H, olefin), 6.03 (d, 1H, olefin), 5.99 (d, 1H, olefin), 5.47 (d, 1H, olefin and m, 13H, $O_{2,3}$H of CD), 4.84 (m, 6H C_1H of CD), 4.45 (m, 5H, O_6H of CD), 3.54 (m, overlaps with HOD). MALDI-TOF MS; *m*/*z* = 1048.7 ($[C_{39}H_{63}NO_{30} + Na]^+$ = 1048.3), 1065.9 ($[C_{39}H_{63}NO_{30} + K]^+$ = 1064.4).

Preparation of AAm-βCD. 6-Amino-β-CD (2.1 g, 1.8 mmol) was dissolved in 100 mL of $NaHCO_3$ aq. (760 mg) and pH of the solution was adjusted to around 10 with NaOH. Acryloyl chloride (350 μL, 4.3 mmol) was added to the solution of 6-amino-β-CD on ice bath. The solution was stirred for 4 hours on ice bath. After the prescribed time, the solution was evaporated to 40% of the total volume and poured into acetone (1 L). The precipitate was collected by centrifugation, and then dried with vacuum oven for an overnight. The crude product was purified by reversed phase chromatography using HP-20 polystyrene gel (methanol/water) to give acrylamide β-CD (820 mg, 40%). ^{1}H NMR (500 MHz, DMSO-d_6): δ 7.90 (t, 1H, amide), 6.26 (dd, 1H, olefin), 6.03 (d, 1H, olefin), 5.65 (d, 1H, olefin and m, 13H, O2,3H of CD), 4.82 (m, 6H C_1H of CD), 4.41 (m, 5H, O_6H of CD), 3.43 (m, overlaps with HOD). MALDI-TOF MS ; *m*/*z* = 1210.4 ($[C_{45}H_{73}NO_{35} + Na]^+$ = 1210.4), 1226.4 ($[C_{45}H_{73}NO_{35} + K]^+$ = 1226.4).

Preparation of AAm-Ad. 1-Adamantylamine (0.76 g, 5.0 mmol) and triethylamine (770 μL, 5.5 mmol) were dissolved in 40 mL of dried THF on ice bath. Acryloyl chloride was added to the solution of 1-adamantylamine (450 μL, 5.5 mmol) on ice bath. The solution was stirred for 4 hours on ice bath. The precipitate was removed by the filtration, and the supernatant was concentrated under the reduced pressure. The obtained crude product was purified by a recrystallization from chloroform (0.85 mg, 83%). ^{1}H NMR (500 MHz, DMSO-d_6): δ 6.15 (dd, 1H, olefin), 5.96 (dd, 1H, olefin), 5.56 (dd, 1H, olefin), 5.15 (brs, 1H, NH), 2.06 (m, 9H, adamantane), 1.59 (m, 6H, adamantane). MALDI-TOF MS ; *m*/*z* = 228.6 ($[C_{13}H_{19}NO + Na]^+$ = 228.1), 244.4 ($[C_{13}H_{19}NO + K]^+$ = 244.1). Elemental Anal. Calcd for $C_{13}HNO(H_2O)_{0.16}$: C, 74.09; H, 9.24; N,6.64. Found: C, 74.06; H, 9.18; N, 6.61.

2-3. Results and discussion

Preparation of Host-Guest Gels. Figures 2-1 depicts the preparation scheme of the supramolecular hydrogels using host-guest polymers. Prior to radical copolymerization, hydrophobic guest monomers (*n*-butyl acrylate (*n*BuAc) and *N*-adamantane-1-yl-acrylamide (AAm-Ad)), which are insoluble in water, were dissolved in corresponding aqueous solutions of acrylamide-CDs (6-AAm-CDs) to form inclusion complexes. The supramolecular hydrogels were prepared by homogeneous radical copolymerization of the inclusion complex with acrylamide (AAm) in water using ammonium peroxodisulfate (APS) as an initiator and *N*,*N*,*N*′,*N*′-tetramethylethane-1,2-diamine (TEMED) as a cocatalyst. After polymerization, the homogeneous solutions yielded hydrogels (Figure 2-2), which were purified by washing with dimethylsulfoxide (DMSO) and water several times.

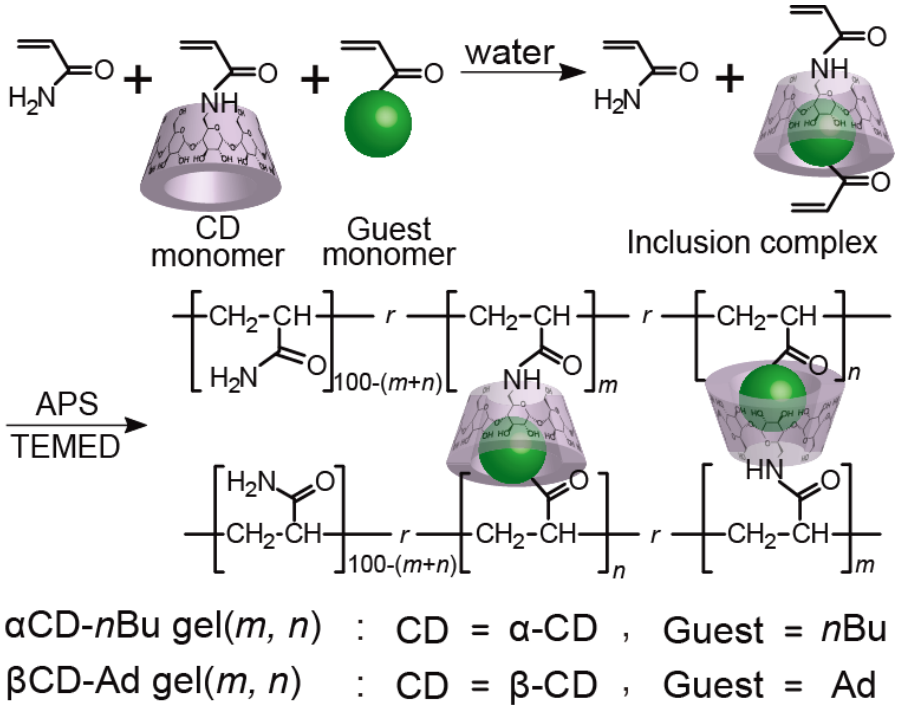


Figure 2-1. Preparation of host-guest supramolecular hydrogels of the αCD-*n*Bu gel(*m*, *n*) and the βCD-Ad gel(*m*, *n*).

The αCD-*n*Bu gel(*m*, *n*) was prepared by homogeneous radical copolymerization of a mixture of 6-AAm-αCD with *n*BuAc in water. Similarly, the βCD-Ad gel(*m*, *n*) was prepared by polymerization of an inclusion complex of 6-AAm-βCD with AAm-Ad. *m* and *n* denote the mol% of the host unit and guest unit, respectively (Figure 2-2). When a mixture of 6-AAm-CD and an aliphatic monomer with AAm in water is heterogeneously polymerized with the same initiator, heterogeneous radical copolymerization does not produce a hydrogel. The homogeneous radical copolymerization in DMSO does not produce a gel even if DMSO in the polymer solution is replaced with water, indicating that the formation of inclusion complexes plays an important role in the formation of a supramolecular hydrogel.

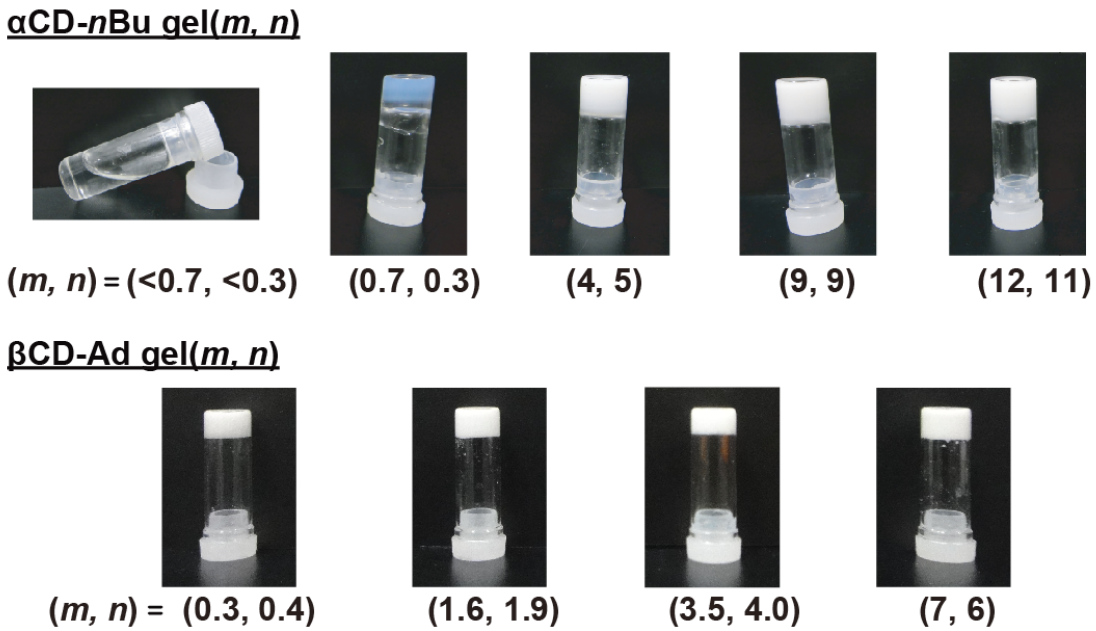


Figure 2-2. Photographs of the αCD-*n*Bu gel(*m, n*) and the βCD-Ad gel(*m, n*) with various mol% of CD and aliphatic guest units.

Figure 2-2 shows photographs of the αCD-*n*Bu gel(*m*, *n*) and the βCD-Ad gel(*m*, *n*). ^{1}H NMR studies showed that an approx. 1:1 molar ratio of host (*m*) and guest (*n*) units is incorporated into the CD–guest gels, implying that homogeneous radical copolymerization is due to a dissolving effect of the inclusion complexes between the CD and guest monomers

(Figure 2-3). The αCD-*n*Bu gel(< 0.7, < 0.3) has a fluid property, whereas αCD-*n*Bu gels(*m*, *n*), which have a higher molar ratio of host (*m*) and guest (*n*), change to self-standing hydrogels. The βCD-Ad gel(*m*, *n*) forms stable self-standing hydrogels even with low contents of CD and Ad units. Although these supramolecular hydrogels lack covalently crosslinked units, the αCD-*n*Bu gel(*m, n*) and the βCD-Ad gel(*m*, *n*) form self-standing gels whose properties can be characterized quantitatively by gel permeation chromatography (GPC) and dynamic viscoelastic measurements.

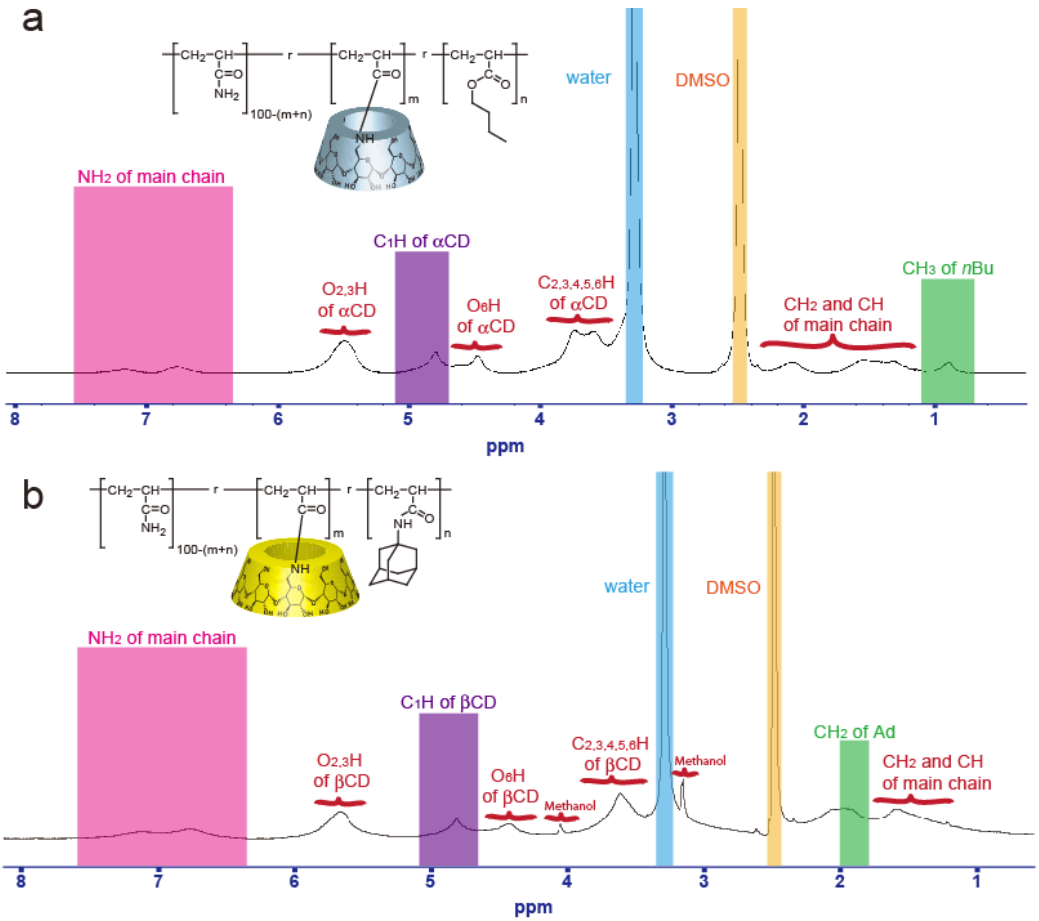


Figure 2-3. 500 MHz ^{1}H NMR spectra of (a) αCD-*n*Bu gel(*m*, *n*) and (b) βCD-Ad gel(*m*, *n*) in DMSO-d_6 at 30 ^{o}C.

Characterizations and mechanical properties of host-guest gels(*m, n*). Prior to the dynamic viscoelastic measurement of the CD-guest gels (the concentration value of each gel was 20 wt%), the molecular weight and polydispersion of the polymers in the gels were determined by GPC using formamide with lithium bromide (LiBr) as an eluent. Although chemically crosslinked gels do not usually dissolve in any solvent, the CD-guest gels dissolve in formamide due to the lack of covalent crosslinkers. GPC analyses of the gels showed that there was no significant difference in molecular weight between the βCD-Ad gel(*m*, *n*) (average M_n = 37,000) and the αCD-*n*Bu gel(*m*, *n*) (average M_n = 25,000) (Table 2-1). On the basis of molecular weight analyses, CD-guest gels were characterized by dynamic viscoelastic measurements.

Table 2-1. Characterizations and mechanical properties of host-guest gels(*m, n*).

Sample	$M_n \times 10^4$ [a] [g mol^{-1}]	M_w / M_n [a]	G' [b] [kPa]	G'' [b] [kPa]
αCD-*n*Bu gel(0.7, 0.3)	2.3	1.3	$2.8 \times 10^{-2} \pm 2.1 \times 10^{-3}$	$2.8 \times 10^{-3} \pm 3.4 \times 10^{-4}$
αCD-*n*Bu gel(4.0, 5.0)	2.5	1.5	$4.0 \times 10^{-2} \pm 2.3 \times 10^{-3}$	$5.8 \times 10^{-2} \pm 8.0 \times 10^{-4}$
αCD-*n*Bu gel(9.0, 9.0)	2.2	1.8	$2.4 \times 10^{-1} \pm 3.1 \times 10^{-2}$	$5.3 \times 10^{-2} \pm 1.2 \times 10^{-2}$
αCD-*n*Bu gel(12, 11)	3.0	2.0	$3.3 \times 10^{-1} \pm 5.4 \times 10^{-2}$	$8.8 \times 10^{-2} \pm 1.6 \times 10^{-2}$
βCD-Ad gel(0.3, 0.4)	3.4	1.2	$9.6 \times 10^{-1} \pm 1.7 \times 10^{-2}$	$1.9 \times 10^{-1} \pm 5.1 \times 10^{-2}$
βCD-Ad gel(1.6, 1.9)	3.6	1.8	$2.0 \times 10^{1} \pm 1.3 \times 10^{1}$	$1.3 \times 10^{1} \pm 9.0 \times 10^{0}$
βCD-Ad gel(3.5, 4.0)	4.0	1.7	$2.4 \times 10^{2} \pm 4.3 \times 10^{1}$	$6.2 \times 10^{1} \pm 4.2 \times 10^{1}$
βCD-Ad gel(7.0, 6.0)	3.9	2.5	$6.8 \times 10^{2} \pm 2.6 \times 10^{1}$	$1.8 \times 10^{2} \pm 1.2 \times 10^{1}$

[a] M_n and M_w/M_n are determined by GPC in formamide calibrated by polystyrene sulfonate Na standards. [b] G' and G'' are obtained by dynamic viscoelatic measurement in condition of strain 0.1% and 25 ^{o}C.

Figure 2-4 shows the storage elastic modulus (G') and loss elastic modulus (G'') for the αCD-*n*Bu gel(*m*, *n*) and the βCD-Ad gel(*m*, *n*). Figure 2-5 summarizes G' and G'' of the αCD-*n*Bu gel(*m*, *n*) and the βCD-Ad gel(*m*, *n*) at a frequency of 10 rad s^{-1}, respectively. The values of G' for the αCD-*n*Bu gel(*m*, *n*) and the βCD-Ad gel(*m*, *n*) do not relax ($G' > G''$) in the frequency range 0.1 – 100 rad s^{-1}. In contrast, the values of G' and G'' increase as the

number of AAm-CD and aliphatic units increase in the supramolecular hydrogels (Figure 2-6), suggesting that the non-covalent crosslink density of the CD-guest gels increases as the mol% of the AAm-CD and guest units increase. The elastic modulus of the βCD-Ad gel(7, 6) is 100 to 1,000 times larger than that of the αCD-*n*Bu gel(12, 11), which is consistent with the association constants of CDs with aliphatic guest molecules. The association constant of α-CD with an *n*Bu group is K_a = 57 M^{-1}, whereas that of β-CD with an Ad group is K_a = 1,500 M^{-1}. These results indicate that the elastic modulus of the CD-guest gels increases as the association constant of the CD with guest units increase.

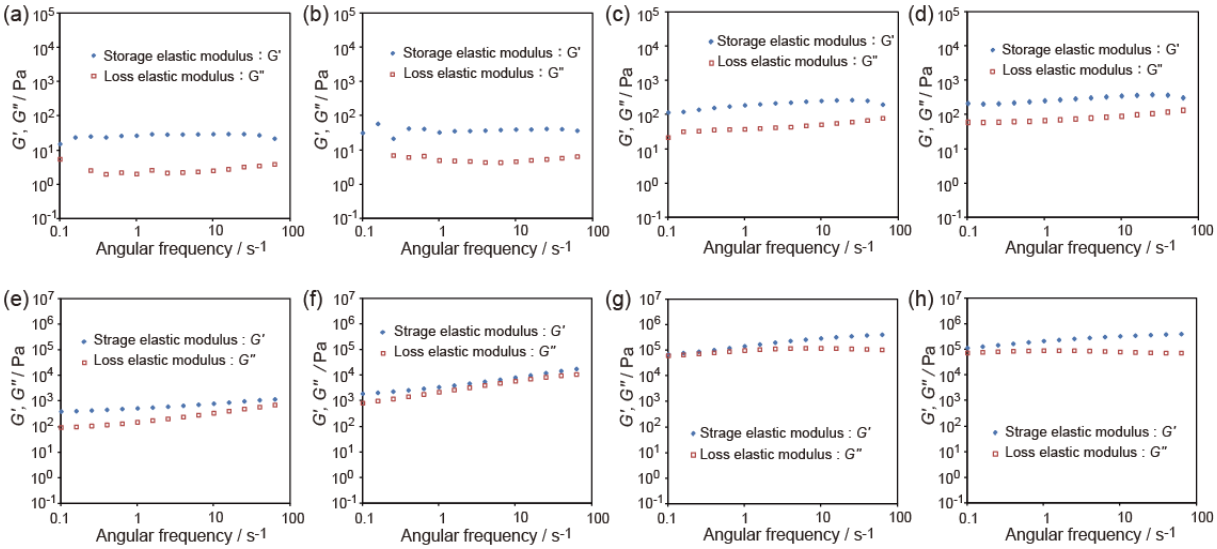


Figure 2-4. *G′* and *G′′* of (a) αCD-*n*Bu gel(3.0, 4.0), (b) αCD-*n*Bu gel(4.0 5.0), (c) αCD-*n*Bu
gel(9.0, 9.0), (d) αCD-*n*Bu gel(12, 11), (e) βCD-Ad gel(0.3, 0.4), (f) βCD-Ad gel(1.6, 1.9), (g) βCD-Ad gel(3.5, 4.0) and (h) βCD-Ad gel(7.0, 6.0). (0.1%, ϕ=15 mm)

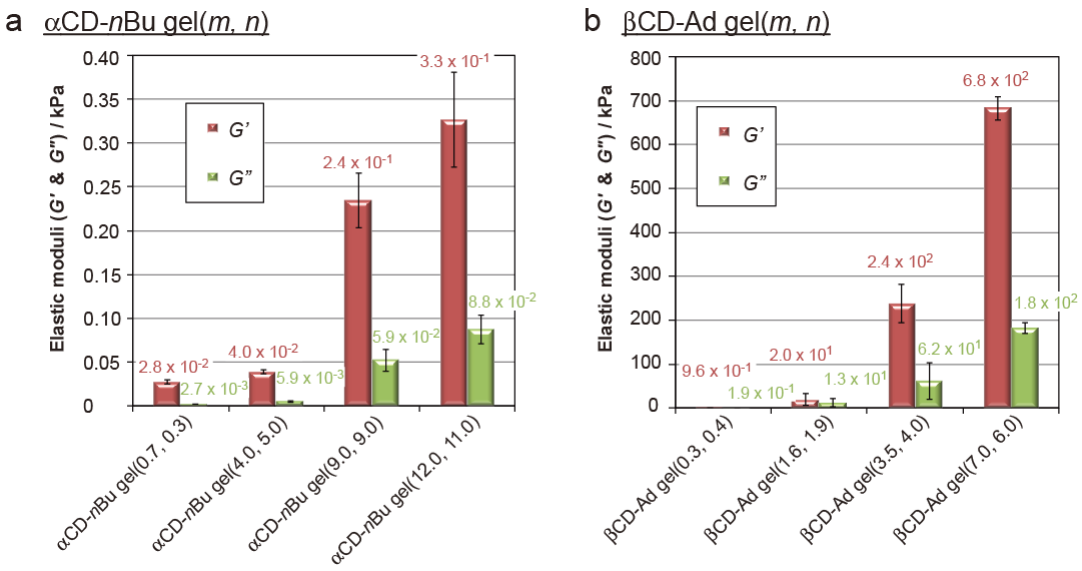


Figure 2-5. Values of the storage elastic modulus (G') and loss elastic modulus (G'') for (a) αCD-*n*Bu gel(*m, n*) and (b) βCD-Ad gel(*m*, *n*).

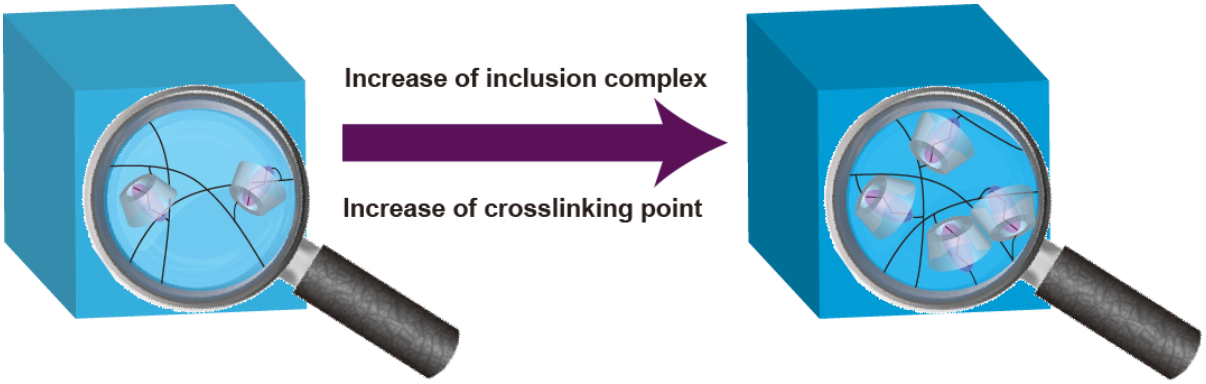


Figure 2-6. Proposed structure of the supramolecular hydrogel. Increasing the CD aliphatic units of supramolecular hydrogels leads to an increase in crosslink density.

Observations of self-healing behavior of the αCD-*n*Bu gel(12, 11) and the βCD-Ad gel(7, 6). CD-guest gels exhibit a self-healing property because the hydrogel has a reversible host-guest interaction between the side chains of the polymers. Cube-shaped CD-guest gels were cut in half using a wedged-shape jig. Figures 2-7 shows the re-adhesion behaviors of the βCD-Ad gel(7, 6) and the αCD-*n*Bu gel(12, 11), respectively. The βCD-Ad gel(7, 6) sample immediately mends after being broken; the gel can be lifted against its own weight. The repaired βCD-Ad gel(7, 6) adheres strongly without a crack after crushing and dropping (Figure 2-8). The αCD-*n*Bu gel(12, 11) sample does not mend immediately, but the two cut pieces reattach to form a single gel after standing for a few hours. These results indicate that the CD and guest units find partners on the cut surface just after attachment, and the strength is sufficient to allow the gel to be lifted up against its own weight.

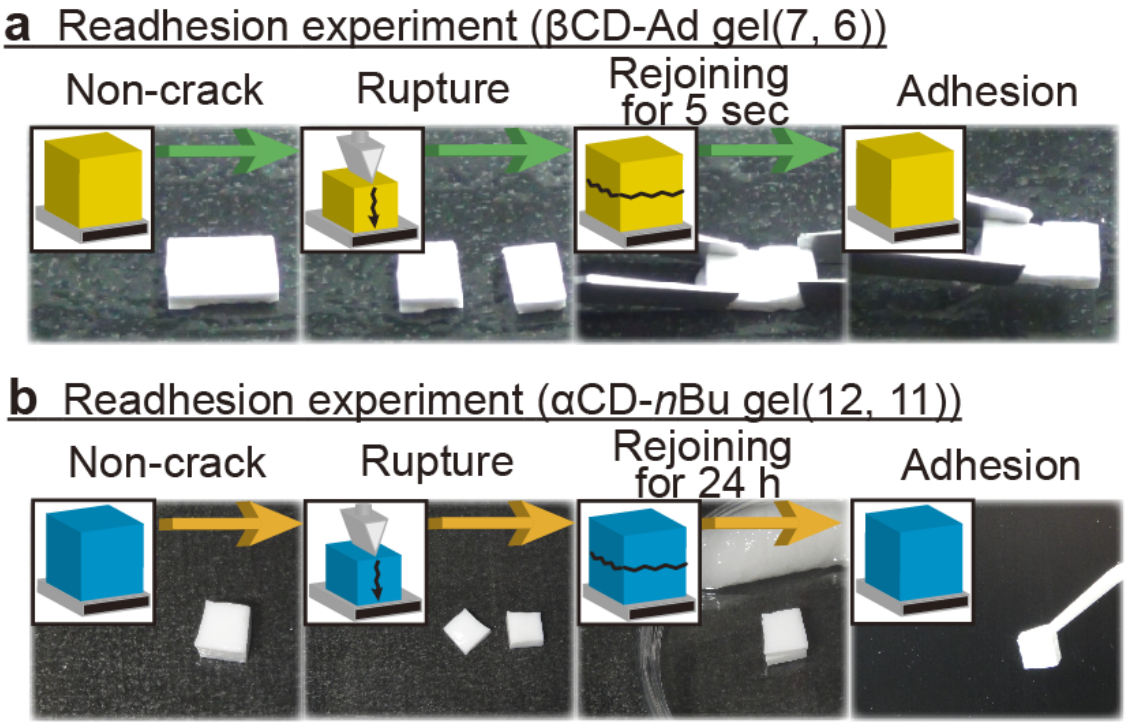


Figure 2-7. Photographs of the self-healing experiments. After standing for 5 s, the two cut (a) βCD-Ad gel(7, 6) and (b)αCD-*n*Bu gel(12, 11) pieces are rejoined, and the crack sufficiently heals to form one gel.

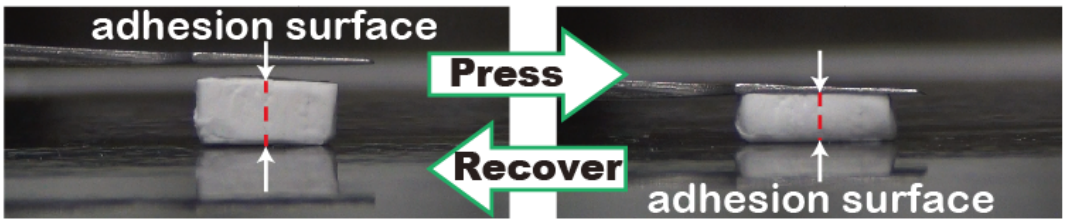


Figure 2-8. Self-healing behavior observed by press test. Healed samples can sustain large deformations. Although scars are not visible, repaired samples break at joints, expect when allowed to heal for a long period.

Competitive experiments of the βCD-Ad gel(7, 6) and the αCD-*n*Bu gel(12, 11). To demonstrate the complementary host-guest interaction between the CD and guest groups, competitive guest or host molecules were added to the cut plane of the CD-guest gels (Figure 2-9). Figure 2-9 shows the competitive experiments of the βCD-Ad gel(7, 6) and the αCD-*n*Bu gel(12, 11). A solution of hexan-1-ol as the competitive guest was placed on the cut surfaces of the αCD-*n*Bu gel(12, 11) (Figure 2-9b). The two cut gels did not adhere within 24 h. Using a similar technique, a solution of αCD as the competitive host was placed on the cut surfaces of the αCD-*n*Bu gel(12, 11). 1-Adamantane carboxylic acid sodium salt (AdCANa, Figure 2-9a) or βCD, in aqueous solutions, were used as the competitive molecules for the βCD-Ad gel(7, 6). In the presence of competitive molecules on the cut surface, the gels do not adhere within 24 h. The competitive molecules inhibit the complexation between the CD and guest units on the cut surface, which function as crosslinkers to adhere the two cut gels.

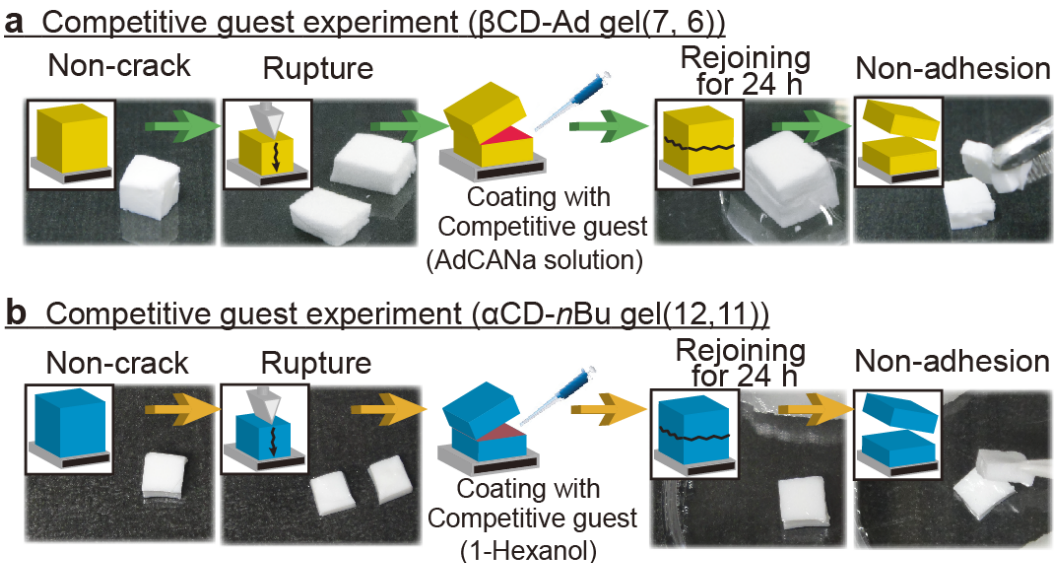


Figure 2-9. Photographs of the self-healing experiments. (a) Competitive experiment of the βCD-Ad gel(7, 6) using the solution of 1-adamantane carboxylic acid sodium salt (AdCANa). After standing for 24 h, the two cut βCD-Ad gel(7, 6) pieces with AdCANa do not mend. Additionally, (b) the two cut αCD-*n*Bu gel(12, 11) pieces with 1-hexanol do not mend.

Estimation of Stress Healing Ratio of the αCD-*n*Bu gel(12, 11) and βCD-Ad gel(7, 6). The author investigated the adhesion ability between cut and uncut surfaces. The two cut βCD-Ad gel(7, 6) pieces show the adhesion behavior of a cut surface. When two uncut surfaces of CD–guest gels are placed in contact with each other, the gels do not adhere. In addition, contact between a freshly cut and uncut surface for 24 h does not mend the gels. In contrast, when two freshly cut surfaces are attached to each other, the gels mend immediately, indicating that free host and guest units on the gel surfaces play important roles in adhesion. These results strongly suggest that the self-healing property is due to complexation of the guest with the CD groups on the cut hydrogel surfaces. The wedged-shape strain compression test analyzed the quantitative adhesive strength of the two gels. First, a rupture experiment determined the initial stress strength (S_0) of each gel. The recovery ratio of the adhesive strength (S_1/S_0) was then calculated using the adhesive strength (S_1) on the joint surface (Figure 2-10a). Figures 2-10b and 2-10c show S_1/S_0 of the

αCD-*n*Bu gel(12, 11) and the βCD-Ad gel(7, 6) as a function of time, respectively. Longer adhesive times give a higher recovery ratio of the rupture strength of CD-guest gels. Upon rejoining two pieces of the αCD–*n*Bu gel(12, 11), the adhesive strength on the joint surface increases over time; after standing for 24 h, 74% of the initial strength is restored (Figure 2-10b). In contrast, upon rejoining two pieces of the βCD-Ad gel(7, 6), the adhesive strength on the joint surface reaches 99% of the initial strength, indicating that two pieces of the βCD-Ad gel(7, 6) quantitatively repair to the initial strength (Figure 2-10c).

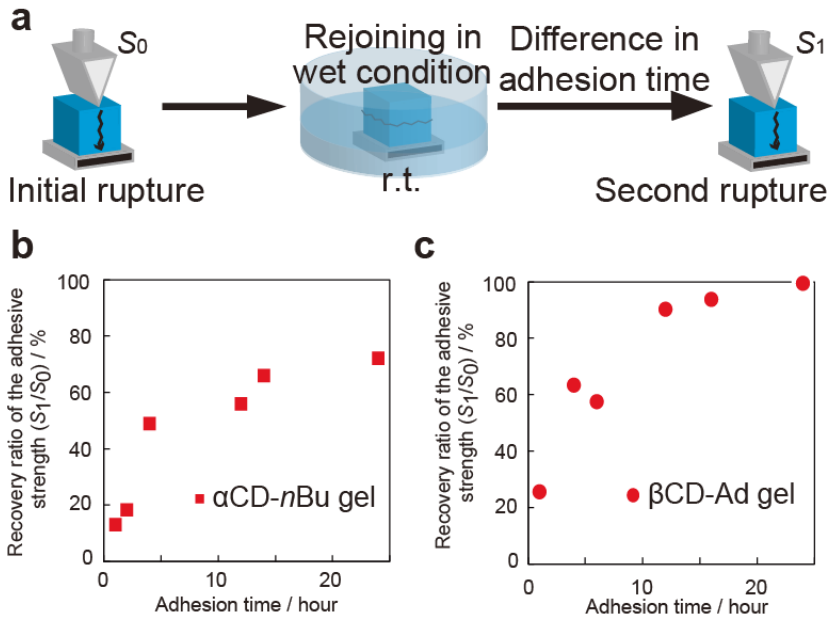


Figure 2-10. Recovery of the adhesive strength of CD-guest gels as a function of time. (a) Evaluation procedure of the self-healing properties of CD-guest gels. First the gel is cut using a wedged-shape jig to determine the initial stress strength (S_0). The two gels are then rejoined and allowed to sit for a certain period before the adhesion strength (S_1) on the joint surface is determined. Recovery ratio of the adhesive strength S_1/S_0 of (b) a αCD-*n*Bu gel(12, 11) and (c) a βCD-Ad gel(7, 6) as a function of time.

The above adhesive experiments were carried out promptly after being cut. However, the author also investigated the effect of waiting to mend two gel pieces on the adhesion strength. Figure 2-11 shows the adhesive strength of the βCD-Ad gel(7, 6) as a function of waiting time between cutting and rejoining. After cutting and standing for a predetermined

time, two gel pieces were placed in contact for 24 h. A rupture experiment determined S_1/S_0 for each case (Figure 2-11a). After a waiting time of 24 h, S_1/S_0 of the βCD-Ad gel(7, 6) reached 84% of the initial strength, indicating that S_1/S_0 of the βCD-Ad gel(7, 6) does not degrade significantly even after sitting for a long time (Figure 2-11b). These results indicate that free guest or host molecules on a cut surface form a complementary complex or recombine to the thermodynamically most stable state (Figure 2-11c).

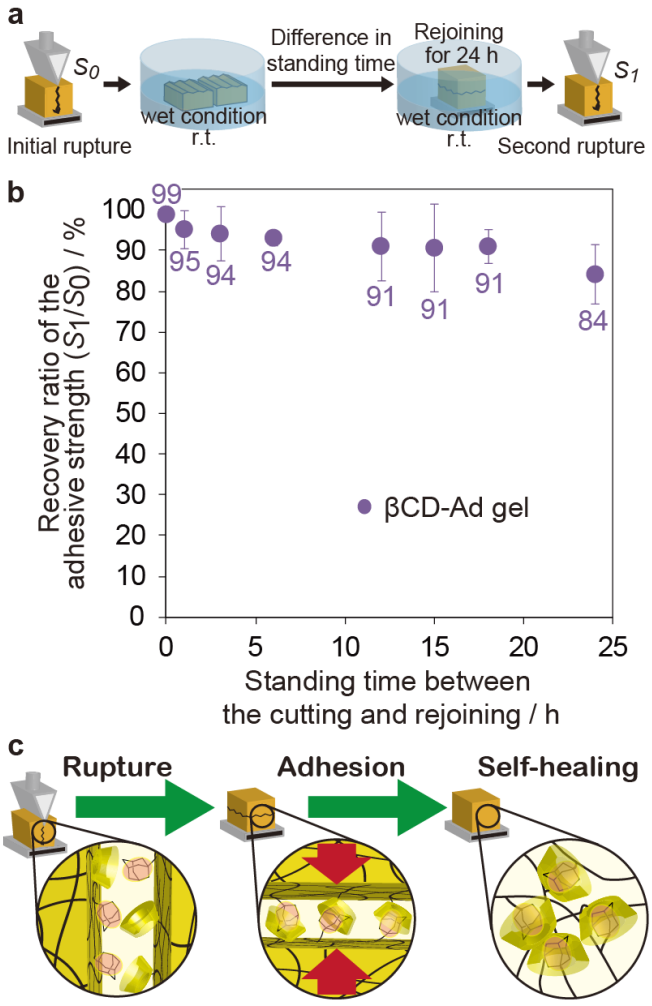


Figure 2-11. Recovery of the adhesive strength of the βCD-Ad gel(7, 6) as a function of waiting time between cutting and rejoining. (a) Evaluation procedure of the βCD-Ad gel(7, 6). The gel is initially cut using a wedgedshape jig to determine the initial stress strength (S_0), and left to stand for a predetermined period. The two gels are then rejoined and allowed to sit for 24 h. (b) Recovery ratio of the adhesive strength (S_1/S_0) of the βCD-Ad gel(7, 6) as a function of waiting time between cutting and rejoining. Self-healing behavior observed by several experiments. (c) Schematic illustration of the self-healing feature.

2-4. Conclusion

In this chapter, the author successfully prepared self-healing CD-guest gels cross-linked between poly(acrylamide) chains with inclusion complexes. The obtained CD-guest gels exhibit a self-standing property without chemical crosslinking reagents, indicating the newly formed host-guest interactions between the CD and the guest units stabilize the conformation of the CD-guest gels. CD-guest gels display selective adhesion between cut surfaces. Healed samples can recover their shape upon releasing the stress. Although scars are not visible, repaired samples break at joints, except when allowed to heal for a long period. Cutting CD-guest gels with a jig breaks the weakest bond, i.e., the host-guest complex. However, when cut surfaces are rejoined, the free CD and guest units on the cut surfaces form inclusion complexes, and the initial stress strength is recovered. Hence, the formation of complementary complexes and the polymerization of inclusion complexes in aqueous solutions play important roles in creating self-healing CD-guest gels. The author believes these healing properties may eventually be used in coating films, plastic containers, and medical materials.

References

1. Dry, C. M. Smart Building Materials Which Prevent Damage and Repair Themselves. In *Smart Materials Fabrication and Materials for Micro-Electro-Mechanical Systems*, Symposium held April 28–30, 1992, San Francisco, CA, vol. 276 in series Materials Research Society Proceedings, MRS Philadelphia: PA, 331, 1992.
2. White, S. R.; Sottos, N. R.; Geubelle, P. H.; Moore, J. S.; Kessler, M. R.; Sriram, S. R.; Brown, E. N.; Viswanathan, S. *Nature* **2001**, *409*, 794.
3. Chen, X.; Dam, M. A.; Ono, K.; Mal, A.; Shen, H.; Nutt, S. R.; Sheran, K.; Wudl, F. *Science* **2002**, *295*, 1698.
4. Toohey, K. S.; Sottos, N. R.; Lewis, J. A.; Moore, J. S.; White, S. R. *Nat. Mater.* **2007**, *6*, 581.
5. Bergman, S. D.; Wudl, F. *J. Mater. Chem.* **2008**, *18*, 41.
6. Wool, R. P. *Soft Matter* **2008**, *4*, 400.
7. Burnworkth, M.; Tang, L.; Kumpfer, J. R.; Duncan, A. J.; Beyer, F. L.; Fiore, G. L.; Rowan, S. J.; Weder, C. *Nature* **2011**, *472*, 334.
8. Dry, C. *Ceram. Trans.* **1991**, *16*, 729.
9. Dry, C. *Smart Mater. Struct.* **1994**, *3*, 118.
10. Dry, C.; Mcmillan, W. *Smart Mater. Struct.* **1996**, *5*, 297.
11. Dry, C. *Cem. Concr. Res.* **2000**, *30*, 1969.
12. White, S. R.; Sottos, N. R.; Geubelle, P. H.; Moore, J. S.; Kessler, M. R.; Sriram, S. R.; Brown, E. N.; Viswanathan, S. *Nature* **2001**, *409*, 794.
13. Kessler, M. R.; White, S. R. *Compos., Part A* **2001**, *32*, 683.
14. Kessler, M. R.; Sottos, N. R.; White, S. R. *Compos., Part A* **2003**, *34*, 743.
15. Brown, E. N.; Sottos, N. R.; White, S. R. *Exp. Mech.* **2002**, *42*, 372.
16. Brown, E. N.; Kessler, M. R.; Sottos, N. R.; White, S. R. *J. Microencapsulation* **2003**, *20*, 719.
17. Brown, E. N.; White, S. R.; Sottos, N. R. *J. Mater. Sci.* **2004**, *39*, 1703.
18. Jones, A. S.; Rule, J. D.; Moore, J. S.; White, S. R.; Sottos, N. R. *Chem. Mater.* **2006**, *18*, 1312.
19. Chen, X.; Dam, M. A.; Ono, K.; Mal, A.; Shen, H.; Nutt, S. R.; Sheran, K.; Wudl, F. *Science* **2002**, *295*, 1698.
20. Chen, X.; Wudl, F.; Mal, A. K.; Shen, H.; Nutt, S. R. *Macromolecles* **2003**, *36*, 1802.
21. Liu, Y. L.; Hsieh, C. Y. *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 905.
22. Watanabe, M.; Yoshie, N. *Polymer* **2006**, *47*, 4946.
23. Liu, Y. L.; Chen, Y. W. *Macromol. Chem. Phys.* **2007**, *208*, 224.
24. Gotsmann, B.; Duerig, U.; Frommer, J.; Hawker, C. J. *Adv. Funct. Mater.* **2006**, *16*, 1499.
25. Szalai, M. L.; McGrath, D. V.; Wheeler, D. R.; Zifer, T.; McElhanon, J. R. *Macromolecules* **2007**, *40*, 818.
26. Rowan, S. J.; Cantrill, S. J.; Cousins, G. R. L.; Sanders, J. K. M.; Stoddart, J. F. *Angew. Chem. Int. Ed.* **2002**, *41*, 898.
27. Lehn, J. -M. *Chem. Soc. Rev.* **2007**, *36*, 151.
28. Corbett, P. T.; Leclaire, J.; Vial, L.; West, K. R.; Wietor, J. -L.; Sanders, J. K. M.; Otto, S. *Chem. Rev.* **2006**, *106*, 3652.
29. Maeda, T.; Otsuka, H.; Takahara, A. *Prog. Polym. Sci.* **2009**, *34*, 581.

30. *Supramolecular Polymer Chemistry*, Ed: Harada, A.; Wiley-VCH, Weinhein, Germany **2011**, 231.
31. Brunsveld, L.; Folmer, B. J. B.; Meijer, E. W.; Sijbesma, R. P. *Chem. Rev.* **2001**, *101*, 4071.
32. Fox, J. D.; Rowan, S. J. *Macromolecules* **2009**, *42*, 6823.
33. De Greef, T. F. A.; Smulders, M. M. J.; Wolffs, M.; Schenning, A. P. H. J.; Sijbesma, R. P.; Meijer, E. W. *Chem. Rev.* **2009**, *109*, 5687.
34. Cohen Stuart, M. A.; Huck, W. T. S.; Genzer, J.; Mueller, M.; Ober, C.; Stamm, M.; Sukhorukov, G. B.; Szleifer, I.; Tsukrul, V. V.; Ueban, M.; Winnik, F.; Zauscher, S.; Luzinov, I.; Minko, S. *Nat. Mater.* **2010**, *9*, 101.
35. Chujo, Y.; Sada, K.; Naka, A.; Nomura, R.; Saegusa, T. *Macromolecules* **1993**, *26*, 883.
36. Tsarevsky, N. V.; Matyjaszewski, K. *Macromolecules* **2002**, *35*, 9009.
37. Scott, T. F.; Schneider, A. D.; Cook, W. D.; Bowman, C. N. *Science* **2005**, *308*, 1615.
38. Imato, K.; Nishihara, M.; Kanehara, T.; Amamoto, Y.; Takahara, A.; Otsuka, H. *Angew. Chem. Int. Ed.* **2012**, *51*, 1138.
39. Amamoto, Y.; Kamada, J.; Otsuka, H.; Takahara, A.; Matyjaszewski, K. *Angew. Chem.* **2011**, *123*, 1698; *Angew. Chem. Int. Ed.* **2011**, *50*, 1660.
40. Cordier, P.; Tournilhac, F.; Soulie-Ziakovic, C.; Leibler, L. *Nature* **2008**, *451*, 7925.
41. Burattini, S.; Colquhoun, H. M.; Greenland, B. W.; Hayes, W. *Faraday Discuss.* **2009**, *143*, 251.
42. Burattini, S.; Colquhoun, H. M.; Fox, J. D.; Friedmann, D.; Greenland, B. W.; Harris, P. J. F.; Hayes, W.; Mackay, M. E.; Rowan, S. J. *Chem. Commun.* **2009**, 6717.
43. Burattini, S.; Greenland, B. W.; Merino, D. H.; Weng, W.; Seppala, J.; Colquhoun, H. M.; Hayes, W.; Mackay, M. E.; Hamley, I. W.; Rowan, S. J. *J. Am. Chem. Soc.* **2010**, *132*, 12051.
44. Burnworth, M.; Tang, L.; Kumpfer, J. R.; Duncan, A. J.; Beyer, F. L.; Fiore, G. L.; Rowan, S. J.; Weder, C. *Nature* **2011**, *472*, 334.
45. Wang, Q.; Mynar, J. L.; Yoshida, M.; Lee, E.; Lee, M.; Okuro, K.; Kinbara, K.; Aida, T. *Nature* **2009**, *463*, 339.
46. Harada, A.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Yamaguchi, H. *Nat. Chem.* **2011**, *3*, 34.
47. Nakahata, M.; Takashima, Y.; Yamaguchi H.; Harada, A. *Nat. Commun.* **2011**, *2*, 511.
48. Yamaguchi, H.; Kobayashi, Y.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Harada, A. *Nat. Commun.* **2012**, *3*, 603.
49. Zheng, Y.; Hashidzume, A.; Takashima, Y.; Yamaguchi, H.; Harada, A. *Nat. Commun.* **2012**, *3*, 831.

Chapter 3

Highly Elastic Supramolecular Hydrogels Using Host−Guest Inclusion Complexes with Cyclodextrins

3-1. Introduction

Supramolecular materials[1,2] have recently attracted much attention due to their unique properties, such as stimuliresponsive materials,[3−10] specific mechanical properties[11−14] and self-healing abilities.[15−23] Supramolecular materials show specific mechanical properties because the noncovalent bonds can reversibly connect and disconnect inside these materials. Supramolecular polymeric materials[24] using hydrogen bonds,[16] π−π stacking,[17−19] ions,[20] hydrophobic interactions,[21] and metal−coordination bonds[22,23] have created unprecedented functions. Most recently, the studies using host−gues interactions have been developed supramolecular hydrogels from macrocyclic hosts, including cyclodextrins (CDs)[25−27] and cucurbit[n]urils,[28,29] which have resulted in mechanical properties. There are three basic approaches to prepare supramolecular polymeric materials through host−guest interactions: (1) from linear-type supramolecular polymers, (2) from a mixture of host and guest polymers, and (3) from polymerization of host and guest monomers (Figure 3-1). Previously, Harada et al. reported supramolecular linear polymers from modified cyclodextrins (CDs).[30−33] Additionally, they have prepared supramolecular hydrogels by mixing an aqueous solution of a CD polymer with that of a guest polymer containing azobenzene[34,35] or ferrocene.[36,37] These reports provide us the effectiveness of employing host−guest interactions to obtain functional supramolecular materials. The author hypothesized that supramolecular materials with host−guest complexes without chemical cross-linkers might show specific mechanical properties, such as elasticity, stretching, and

stress recovery properties. To create supramolecular materials with specific mechanical properties, herein the author employs the polymerization of inclusion complexes between CD and guest monomers in aqueous solutions. This method gives supramolecular hydrogels with highly elastic and shape recovery properties.

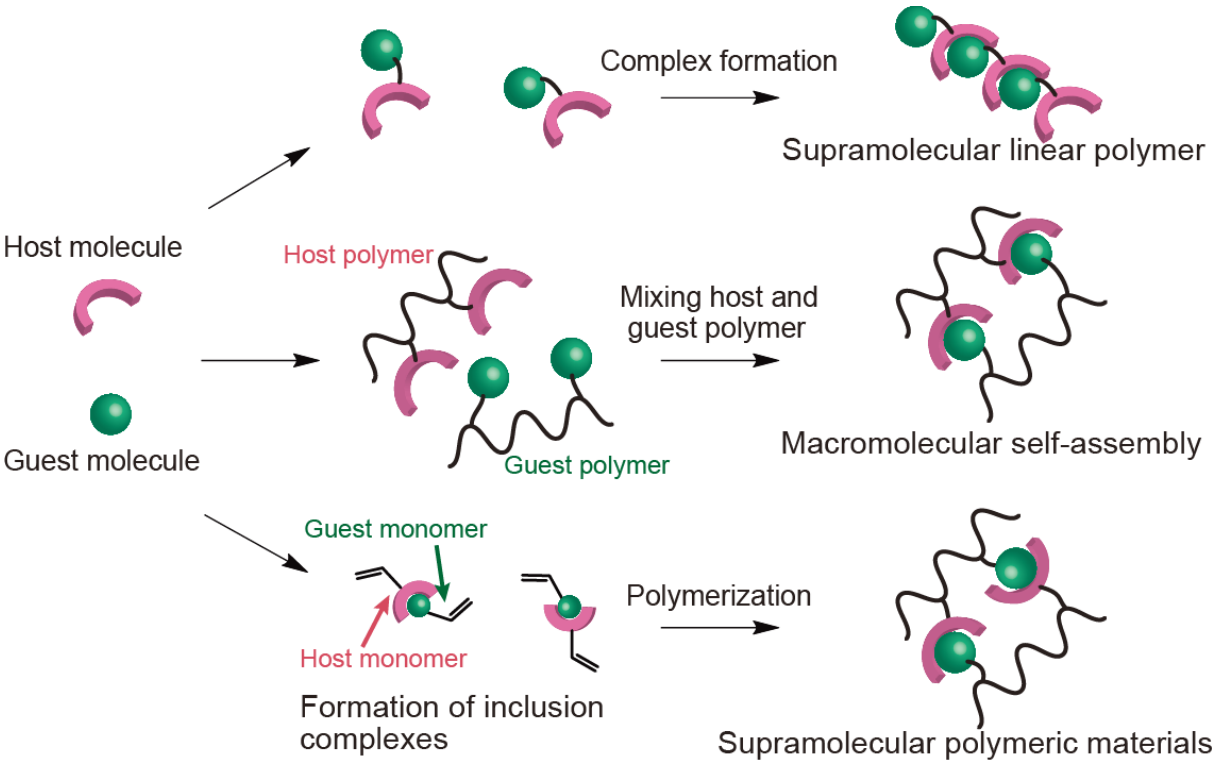


Figure 3-1. Formation of supramolecular polymers. Top: Formation of a supramolecular linear polymer from host molecules with a guest unit. Middle: Macromolecular self-assembly from host and guest polymers. Bottom: Supramolecular polymeric materials prepared by polymerization of preorganized host and guest monomers.

3-2. Experimental Section

General Procedures. β-Cyclodextrin (βCD) was obtained from Junsei Chemical Co., Ltd. sodium hydrogen carbonate ($NaHCO_3$), ammonium peroxodisulfate (APS), 1-Adamantanamine and [2-(dimethylamino)ethyl]dimethylamine (TEMED) were obtained from Nacalai Tesque Inc. Acryloyl chloride was obtained from Tokyo Kasei Inc. DMSO-d_6 was obtained from Merck & Co., Inc. A highly porous synthetic resin (DIAION HP-20) used for column chromatography was purchased from Mitsubishi Chemical Co., Ltd. Water, which was used to prepare the aqueous solutions (except for NMR measurements), was purified with a Millipore Elix 5 system. Other reagents were used as received.

Measurements. One dimensional NMR spectra were recorded with a JEOL ECA-500 NMR spectrometer at 30 ^{o}C. Chemical shifts were referenced to the solvent values (δ = 2.49 ppm for DMSO-d_6). Dynamic viscoelasticity was measured using an Anton Paar MCR301 rheometer at strain of 0.1%. Mechanical properties of the gel were measured by the rupture testing system (Creep meter, RE-33005B, Yamaden Ltd.). The author described all tensile strength as a conventional stress. Ger permeation chromatography (GPC) was performed in formamide (0.30 mL/min) with 0.1% lithium bromide using a TOSOH GPC-8020 Model II equipped with TOSOH TSKgel α-M column to determine molecular weights (M_n). M_n of host-guest gels were measured with respect to polystyrene sulfonate Na salt (PSSNa) standards (American polymer standards Corp., Mentor, Ohio).

Preparation of β-Cyclodextrin Acrylamide as a Host Monomer (AAm−βCD).[39] 6-Amino-βCD (5.0 g, 4.4 mmol) was dissolved in 200 mL of $NaHCO_3$(aq) (1.9 g, 2.2 × 10^1 mmol) and the pH of the solution was adjusted to approximately 10 with NaOH. Acryloyl chloride (4.3 × 102 μL, 5.3 mmol) was added to the solution of 6-amino-βCD in an ice bath.

After stirring the solution for 10 h in an ice bath, the solution was evaporated to 40% of the total volume and poured into acetone (1 L). The precipitate was collected by suction filtration and dried in a vacuum oven (40 °C) overnight. The crude product was purified by reverse phase chromatography using HP-20 polystyrene gel (methanol/water) to give AAm−βCD (3.7 g, 70%). ^{1}H NMR (500 MHz, DMSO-d_6): δ 7.89 (t, 1H, amide), 6.25 (dd, 1H, olefin), 6.00 (d, 1H, olefin), 5.73 (d, 1H, olefin and m, 13H, $O_{2,3}H$ of CD), 4.87 (m, 6H C_1H of CD), 4.45 (m, 5H, O_6H of CD), 3.46 (m, overlaps with HOD). MALDI−TOF MS; *m*/*z* = 1210.39 ($[C_{45}H_{73}NO_{35} + Na]^+$ = 1210.34, 0.004% error), 1226.4 ($[C_{45}H_{73}NO_{35} + K]^+$ = 1226.3, 0.008% error).

Preparation of N-Adamantan-1-yl Acrylamide as a Guest Monomer (AAm−Ad).[30] 1-Adamantanamine (3.1 g, 2.0×10^1 mmol) and triethylamine (3.1 mL, 2.2×10^1 mmol) were dissolved in 300 mL of THF in an ice bath. Acryloyl chloride (1.8 mL, 2.2×10^1 mmol) was added to the solution in an ice bath. The solution was stirred for 2 h in an ice bath followed by stirring overnight as the solution warmed to room temperature. The precipitate was removed by filtration, and the supernatant was evaporated. The obtained crude product was purified by silica gel column chromatography (eluted with hexane/ethyl acetate = 50/50 vol %), and gave 2.3 g of the desired product. Yield: 75%. ^{1}H NMR (500 MHz, $(CD_3)_2SO$): δ 6.15 (dd, 1H, olefin), 5.96 (dd, 1H, olefin), 5.56 (dd, 1H, olefin), 5.15 (brs, 1H, NH), 2.06 (m, 9H, adamantane), 1.59 (m, 6H, adamantane). MALDI−TOF MS; *m*/*z* = 228.6 ($[C_{13}H_{19}NO + Na]^+$ = 228.1, 0.21% error), 244.4 ($[C_{13}H_{19}NO + K]^+$ = 244.1, 0.12% error). Anal. Calcd for $C_{13}H_{19}NO(H_2O)_{0.16}$: C, 74.09; H, 9.24; N, 6.64. Found: C, 74.06; H, 9.18; N, 6.61 (0.18% error).

2-3. Results and discussion

Preparation of βCD−Ad Gels(*m*, *n*). To construct supramolecular hydrogels with a high elasticity, the author selected an adamantane derivative as the guest group because the adamantane derivative is one of the best guest molecules for βCD.[38] Figure 3-2 depicts the chemical structure of the supramolecular hydrogels (βCD−Ad gels(*m*, *n*)). *m* and *n* represent the mol% of β-cyclodextrin acrylamide (AAm−βCD) and *N*-adamantan-1-yl acrylamide (AAm−Ad), respectively. Prior to the preparation of βCD−Ad gel, AAm−Ad was dissolved in water by AAm−βCD to give an inclusion complex. The βCD−Ad gels lack chemical cross-linking molecules, indicating that host−guest interactions stabilize the βCD−Ad gels as noncovalent cross-linkers.

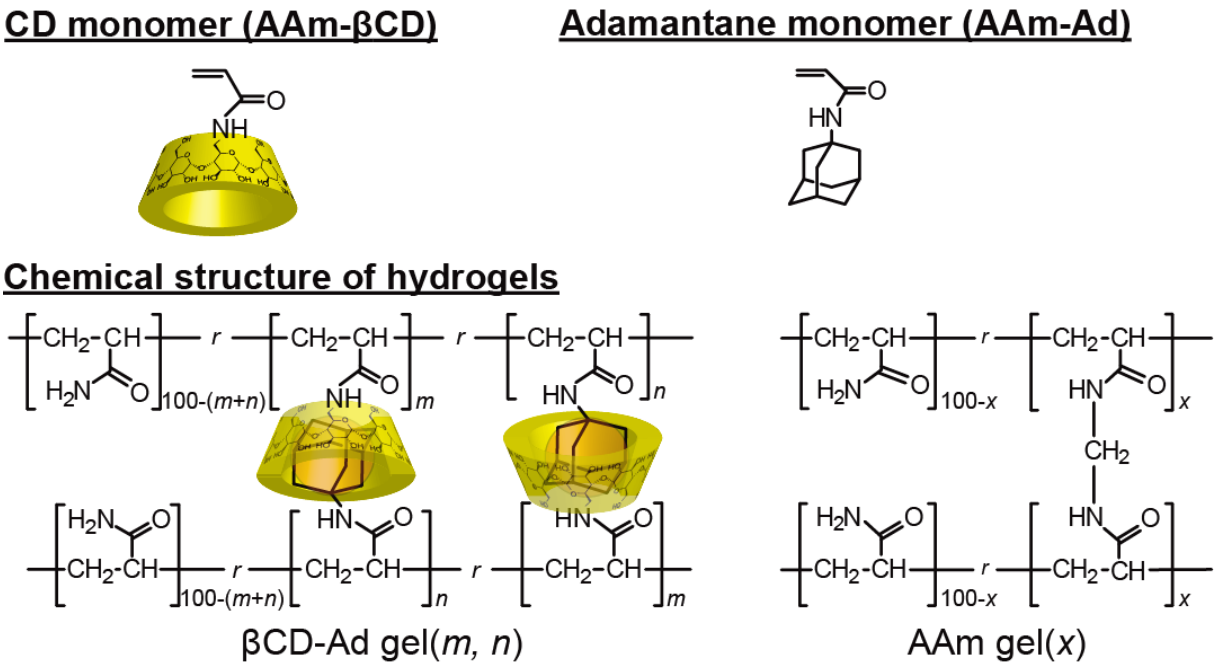


Figure 3-2. Chemical structures of AAm−βCD, AAm−Ad, βCD−Ad gels(*m*, *n*), and AAm gel(*x*).

Figure 3-3 shows photographs of the βCD−Ad gels(*m*, *n*). The viscosity of the βCD−Ad gels increased as the composition ratio (*m*, *n*) increased. Unexpectedly, βCD−Ad gels(*m*, *n*) with low contents of host and guest units formed supramolecular hydrogels. These βCD−Ad gels were stable and did not change morphology over time. When acrylamide (AAm) was polymerized with methylenebis(acrylamide) (MBAAm, <1.0 mol%), they did not produce a hydrogel, but gave a polymeric solution under the same conditions. Additionally, polymerization of AAm−βCD and AAm−Ad in DMSO did not give any hydrogel, because the interaction between βCD and Ad derivatives is significantly low in DMSO, implying that the formation of an inclusion complex between the βCD and Ad units plays an important role in stabilizing the morphology of the βCD−Ad gels. To confirm the effect of complex formation, native βCD was added to the polymerization solution containing AAm−Ad, AAm−βCD, and AAm. The polymerization solution with βCD did not produce a hydrogel, suggesting that βCD inhibits the formation of an inclusion complex between the AAm−βCD and AAm−Ad. The host−guest inclusion complex functions as a cross-link unit in the βCD−Ad gel(*m*, *n*).

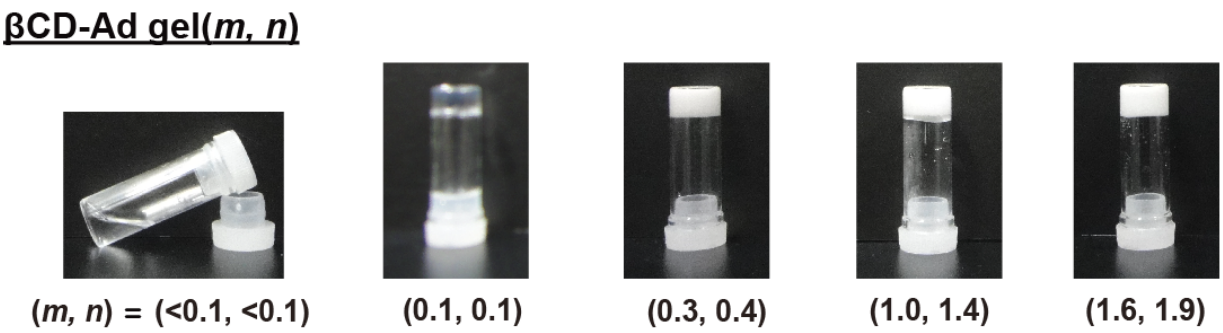


Figure 3-3. Photographs of the βCD−Ad gel(*m*, *n*) with various mol% of CD and Ad guest units. *m* and *n* denote the mol% of the host and guest units, respectively.

Dynamic viscoelastic measurements of βCD-Ad gels(*m, n*). Figures 3-4a and 3-4b show the storage elastic modulus (G') and loss elastic modulus (G'') for βCD-Ad gels. G' values were larger than G'' values in the region of $m > 0.1$ and $n > 0.1$. On the other hand, the G' of the βCD-Ad gel(<0.1, <0.1) was smaller than the G'' (Figure 3-4c). Figure 3-4d shows the elastic moduli of βCD-Ad gel(*m, n*) at 10 rad·s^{-1}. G' and G'' of βCD-Ad gel(*m, n*) increased the values with increasing molar ratio (mol%) of host and guest molecules, suggesting that amount of the non-covalent cross-linker through the host-guest interaction effectively forms inside βCD-Ad gels. Although a reference gel of the AAm gel(1.0) showed $G' > G''$, the AAm gel(0.3>) showed $G' < G''$ (sol state). The βCD-Ad gels with the βCD/Ad inclusion complex do not relax even in the low content (0.3 ~ 1.9) of *m* and *n*.

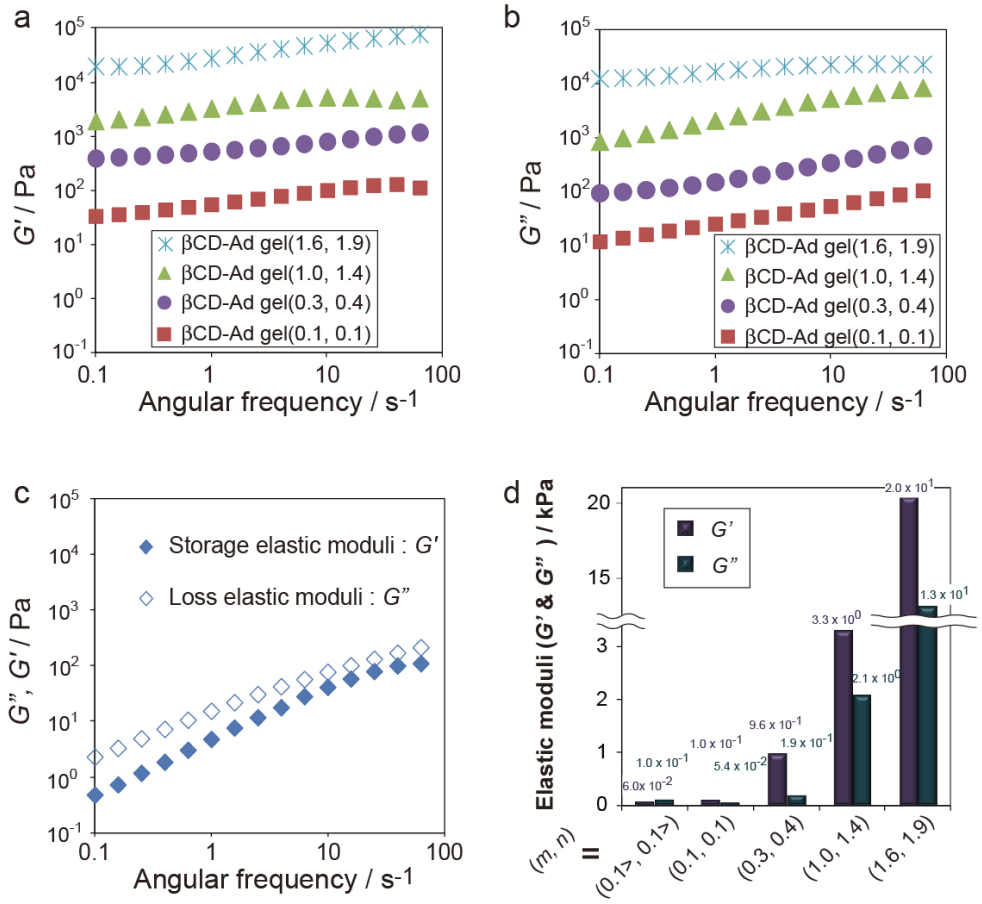


Figure 3-4. The viscoelastic behaviors of βCD-Ad gel(*m, n*). (a): the storage elastic moduli (G'). (b): the loss elastic moduli (G''). (c): the sol state spectra of βCD-Ad gel(0.1>, 0.1>). The G' were lower than G''. (d): Values of G' and G'' for βCD-Ad gel(*m, n*).

Stress−strain behavior of βCD−Ad Gel(*m*, *n*). Figure 3-5a shows the stress−strain curves of the βCD−Ad gels(*m*, *n*) (size: 5 × 5 × 10 mm^3), which were analyzed by a creep meter at a tensile speed of 5 mm/s. The order of the breaking stress was βCD−Ad gel(0.1, 0.1) < βCD−Ad gel(0.3, 0.4) < βCD−Ad gel(1.0, 1.4) < βCD−Ad gel(1.6, 1.9), whereas the breaking strain was βCD−Ad gel(1.6, 1.9) < βCD−Ad gel(1.0, 1.4) < βCD−Ad gel(0.3, 0.4) < βCD−Ad gel(0.1, 0.1). The AAm gel(1.0) showed a low breaking strain value (170%) and no yield point (Figure 3-5b), while the βCD−Ad gel(0.1, 0.1) and βCD−Ad gel(0.3, 0.4) showed a breaking strain value of 990% and 960%, respectively, even with low host and guest unit contents. The βCD−Ad gel(0.3, 0.4) exhibited a clear yield point at 220% strain. Increase in the host and guest contents increased the breaking stress. These results indicate that the strength of βCD−Ad gels(*m*, *n*) is related to the number of the inclusion complexes as cross-linkers because the complex formation provides stretching properties.

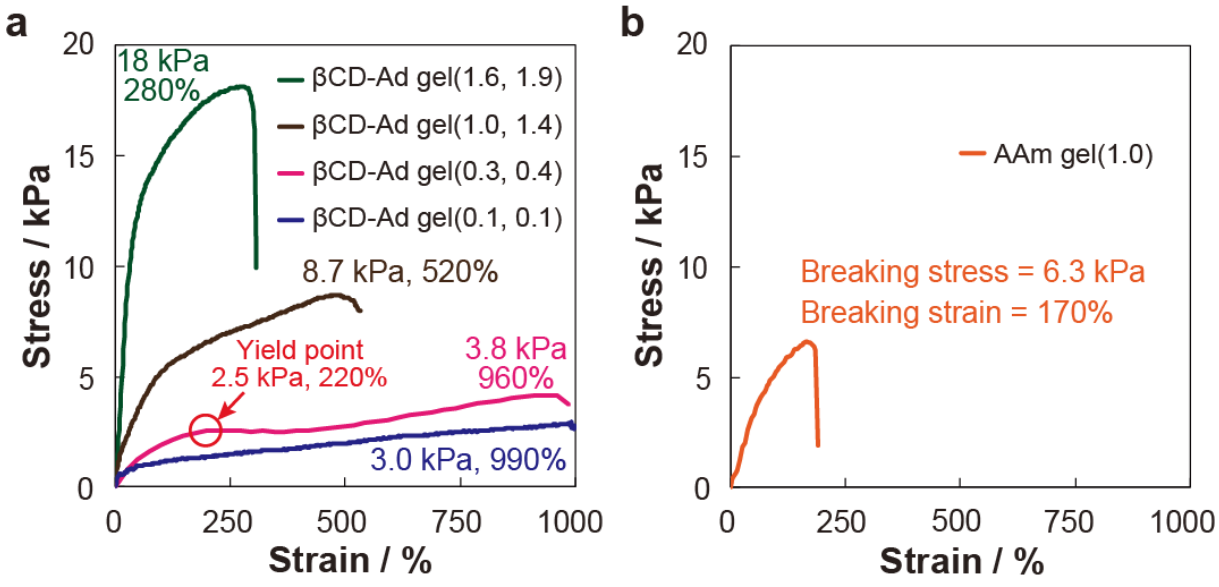


Figure 3-5. Stress−strain curves of βCD−Ad gels(*m*, *n*) (a) and Stress−strain curve of the AAm gel(1.0) (b).

To evaluate the relationship between the number of crosslinkers (inclusion complexes) and the mechanical properties of the gel materials, the author investigated the influence of competitive molecules on the physical property of βCD−Ad gels(*m*, *n*). Figure 3-6a shows the stress−strain curves of βCD−Ad gels(*m*, *n*) after immersing in a βCD aqueous solution (10 mM) as a competitive host for an hour. The breaking stress decreased to about 55−75% of the initial stress. Figure 3-6b shows the breaking stress values of the βCD−Ad gel(*m*, *n*) when the βCD−Ad gels are immersed in an aqueous solution of βCD or 1-adamantane carboxylic acid sodium salt (AdCANa). The breaking stress values of the gels decreased from the initial stress values. On the other hand, when immersed in an aqueous solution of αCD or γCD, the stress values did not significantly decrease. Previous studies have suggested that the association constant of Ad for βCD is larger than those for αCD and γCD (αCD/Ad: K_a = 98 M^{-1}; βCD/Ad: K_a = 1500 M^{-1}; γCD/Ad: K_a < 10 M^{-1}).[38] The tensile strength of the βCD−Ad gels immersed in aqueous solutions of αCD or γCD showed no change due to the low affinities of αCD and γCD for Ad derivatives, whereas that of the βCD−Ad gel immersed in aqueous solution of βCD is significantly decreased, indicating that the complementarity between the βCD competitive host molecule and the Ad unit of the βCD−Ad gels leads to the greater the change in tensile strengths. Immersing βCD−Ad gels in 10 mM of AdCANa(aq) leads to a decrease in the tensile strength. The breaking strain of the βCD−Ad gels(*m*, *n*) increased from the initial strain after immersing in an aqueous solution of βCD and AdCANa because the addition of competitive molecules to decompose the inclusion complexes, which function as cross-linkers, causes decreasing cross-link density of βCD−Ad gels. Our results suggest that the mechanical properties of the βCD−Ad gels(*m*, *n*) depend on the number of inclusion complexes through molecular recognition.

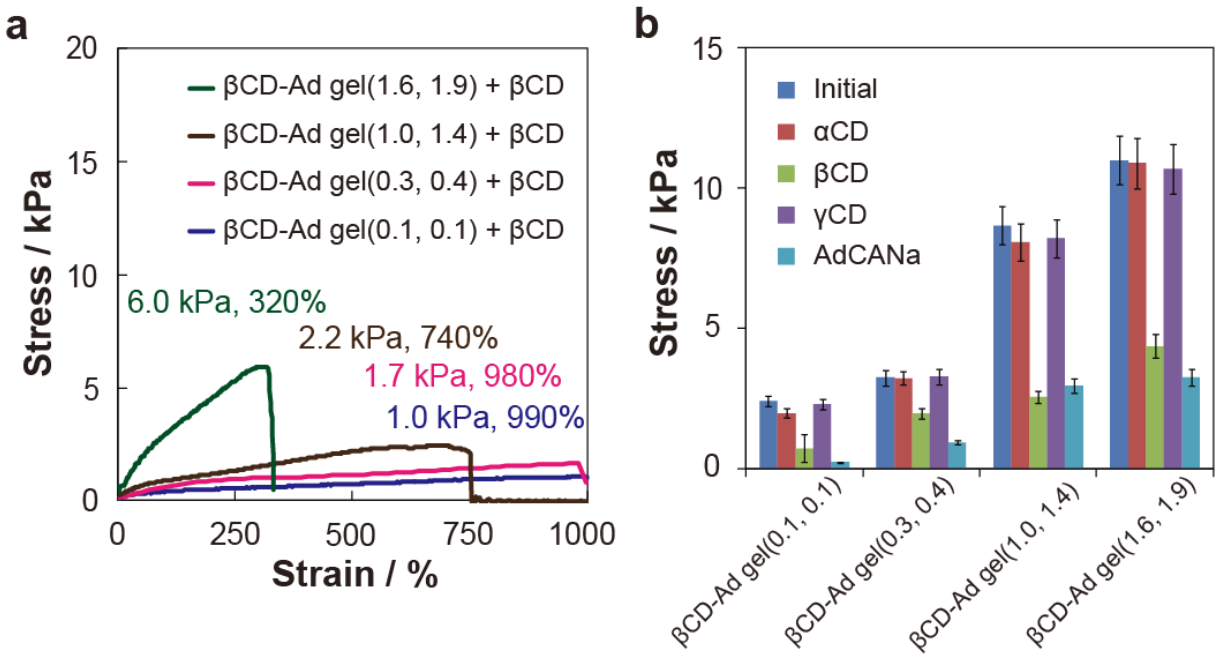


Figure 3-6. (a) Stress−strain curves of βCD−Ad gels(*m*, *n*) after immersing in an aqueous solution of βCD for an hour. (b) Breaking stress values of βCD−Ad gels(*m*, *n*) before and after immersing in aqueous solutions of αCD, βCD, γCD, or AdCANa. More than three independent studies confirmed the stress change of the βCD−Ad gels(*m*, *n*).

Shape Recovery Behavior of βCD−Ad Gel(*m*, *n*). Figure 3-7 shows the tensile test of the βCD−Ad gel(0.3, 0.4) using tweezers. When the rectangular shape of the βCD−Ad gel(0.3, 0.4) was stretched with tweezers and released, the morphology of the βCD−Ad gel(0.3, 0.4) recovered the initial state. However, the βCD−Ad gel(1.6, 1.9) did not show the same behavior. Although the βCD−Ad gel(1.6, 1.9) showed a high breaking stress, the breaking strain is too small to observe the yield point, implying that the βCD−Ad gel(1.6, 1.9) did not possess the stretching and recovering properties, the gel breaks. Additionally, stretching and releasing the AAm gel(1.0) and AAm gel(1.9) did not recover the initial morphologies.

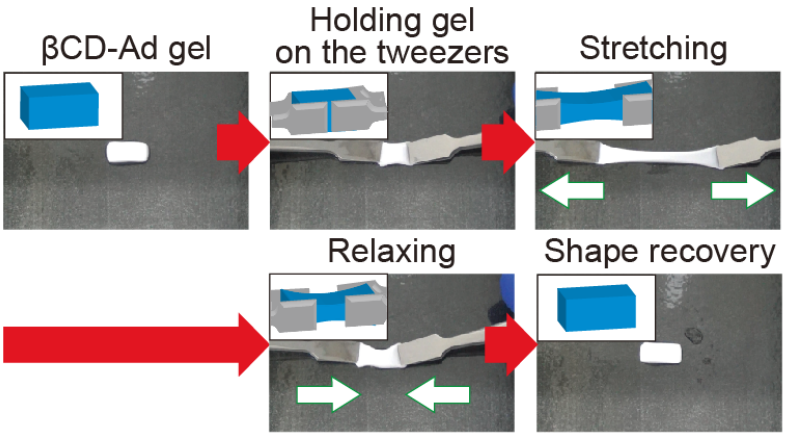


Figure 3-7. Shape recovery behavior of βCD−Ad gel(0.3, 0.4) using tweezers.

Figure 3-8 shows the tensile-relaxation test to observe the shape recovery behavior. First, the βCD−Ad gel(0.3, 0.4) (size: 5 × 5 × 10 mm^3) was stretched by applying load of 0.1 N for 5 s. Then the tensile stress of the βCD−Ad gel(0.3, 0.4) was relaxed to 0 N for 300 s (Figure 3-8a). Figure 3-8b shows the strain-time curve of the βCD−Ad gel(0.3, 0.4). The βCD−Ad gel(0.3, 0.4) stretched to 180% of the initial strain, which is less than the yield point. The strain returned to 0% for βCD−Ad gel(0.3, 0.4) within 300 s. After three cycles, the βCD−Ad gel(0.3, 0.4) still exhibited the shape recovery behavior (Figure 3-8c). In contrast, the AAm gel(1.0) did not recover within 300 s (Figure 3-9a). Figure 3-9a shows the strain−time curve of the AAm gel(1.0). When the AAm gel(1.0) stretched to 84% of the initial strain, which is less than the breaking strain (170%), the AAm gel(1.0) showed 8.4% of the residual strain, indicating that AAm gels have low stretching and recovery properties. Although the βCD−Ad gel(0.3, 0.4) had the shape recovery property, the stretched βCD−Ad gel(0.3, 0,4) to 650% of the initial strain, which is over the yield point, did not recover and showed 50% of the residual strain (Figure 3-9b), suggesting that a tensile below 200% of the yield point of the strain achieves in shape recovery.

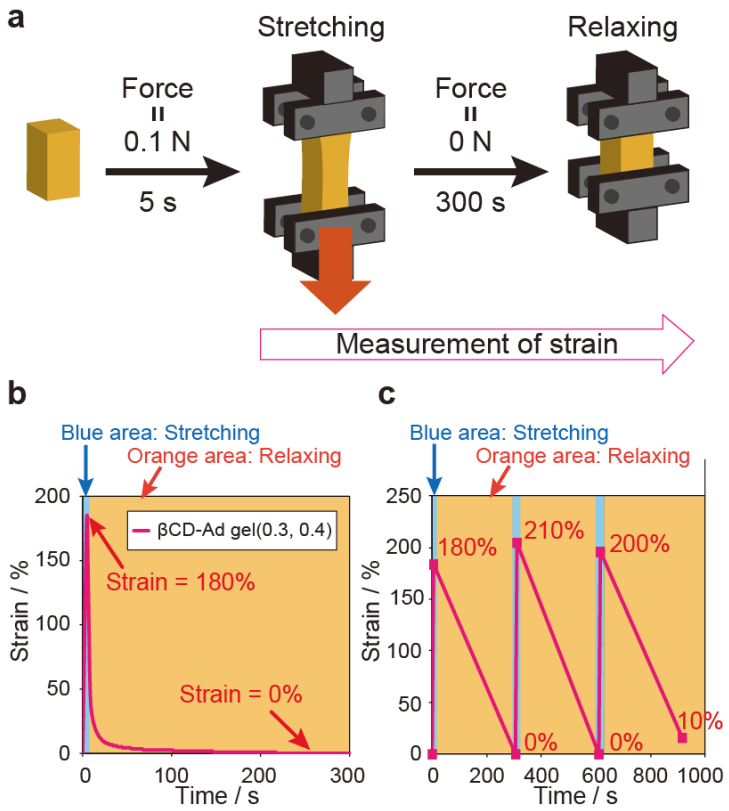


Figure 3-8. (a) Schematic illustration of the tensile-relaxation test by a creep meter. (b) Time-strain curve of the βCD−Ad gel(0.3, 0.4) when stretching from the initial strength by applying a load of 5.9 kPa (0.1 N, 25 mm^2) for 5 s and subsequent relaxation by applying a load of 0 N for 300 s. (c) Cyclic experiment of the βCD−Ad gel(0.3, 0.4) under the same conditions each time.

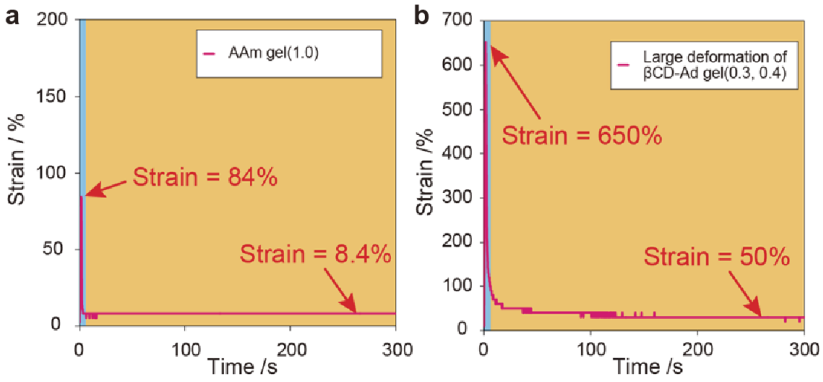


Figure 3-9. (a) Time-Strain curve of the AAm gel(1.0) in condition of stretching from initial strength by (Blue) applying load of a 4.4 kPa (0.1 N, 25 mm^2) for 5 seconds and then (Orange) relaxing. (b) Time-Strain curve of the βCD-Ad gel(0.3, 0.4) by over 600% of the strain in condition of stretching from initial strength by (Blue) applying load of a 8.1 kPa (0.2 N, 25 mm^2) for 5 seconds and then (Orange) relaxing.

Figure 3-10 shows the proposed mechanism for the breaking behavior of the βCD−Ad gel(0.3, 0.4) in the tensile test. In the recovery region, which is the strain region up to the yield point, the βCD−Ad gel(0.3, 0.4) recovers to the initial shape after releasing of the stress (0.1 N). When deformation of the gel, most of the inclusion complexes change conformations, some decompose. Upon releasing the stress, the dissociated CD and Ad units reform the initial complex, and eventually the initial shape is restored. The plastic deformable region is higher than the yield point in the strain. The deformation is too large to repair the initial form and inclusion complexes. However, when releasing the stress, free host and guest molecules find nearby partners to form an inclusion complex as noncovalent crosslinkers. Therefore, the deformed gels do not relax. Finally, in the breaking region, the host−guest complexes completely decomposes, and the gel is broken.

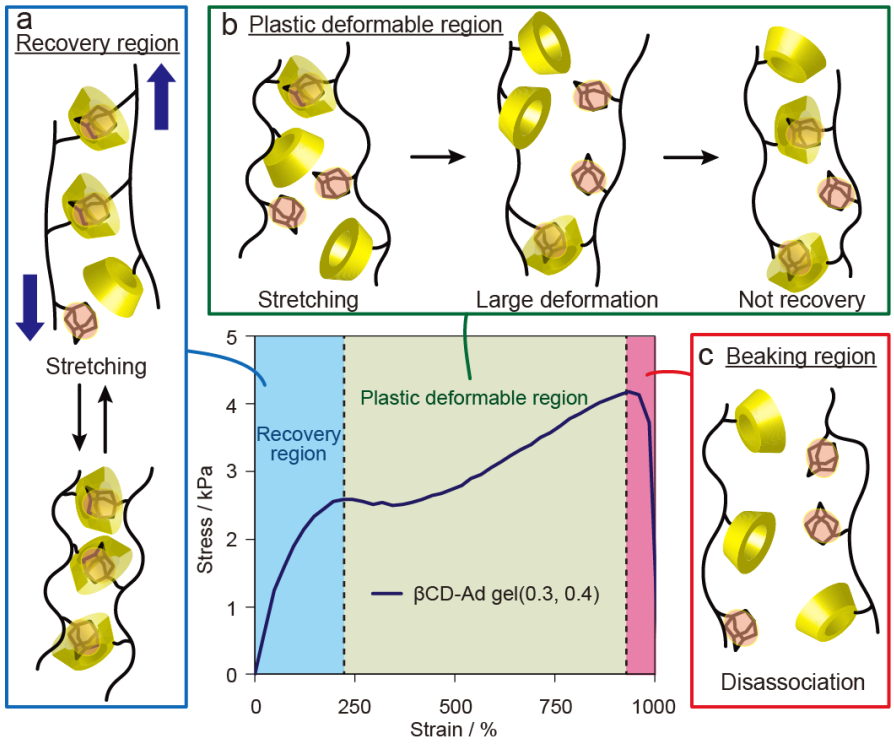


Figure 3-10. Stress−strain curve of the βCD−Ad gel(0.3, 0.4) and proposed mechanism for the shape recovery behavior in the βCD−Ad gel(0.3, 0.4). (a) Recovery region: the βCD−Ad gel(0.3, 0.4) is stretched up to the yield point of the strain. Although some of the CD−Ad complex dissociates upon stretching, after releasing the stress (0.1 N), the CD−Ad complex recovers the initial material strength. (b) Plastic deformable region: the βCD−Ad gel(0.3, 0.4) is stretched beyond the yield point. Although the large deformation prevents the dissociated CD−Ad complex from reforming the initial complex, free host and guest molecules find nearby partners to form an inclusion complex. (c) Breaking region: the CD−Ad complex is dissociated by the large deformation.

2-4. Conclusion

The author successfully prepared a highly elastic hydrogel via host−guest interactions using cyclodextrin and adamantane as host and guest molecules, respectively. The βCD and Ad inclusion complex acts as a supramolecular cross-linker, stabilizing the βCD−Ad gels(<0.1, <0.1) without a chemical cross-linker. On the other hand, poly(acrylamide) gel, which lacks a supramolecular cross-linker, does not exhibit stretching and recovery properties. The βCD−Ad gel(0.3, 0.4) shows high stretching (breaking strain: 960%) and high recovery properties (residual strain: 0.0%) within 220% of the yield point even with low contents of host and guest units. The addition of competitive molecules suppresses the stretching and recovery properties. The author expected that the yield points of βCD−Ad gel(<1.0, <1.0) might be smaller than that of AAm gel(1.0) due to noncovalent interaction, but just the unexpected results happened. The supramolecular cross-linker functions as flexible and sacrifice bonds to produce the stretching and recovery properties of βCD−Ad gel(*m*, *n*). Controlling the properties of the host−guest gels creates an innovative use of supramolecular hydrogels; the author believe that these shape-repairing properties could have medical and industrial material applications.

References

1. Calvert, P. *Adv. Mater.* **2009**, *21*, 743.
2. Aida, T.; Meijer, E. W.; Stupp, S. I. *Science* **2012**, *335*, 813.
3. (a) *Electroactive Polymer (EAP) Actuators as Artif icial Muscles - Reality, Potential and Challenges*, 2nd ed.; Bar-Cohen, Y., Ed.; SPIE Press: Bellingham, WA, 2004; (b) *Conductive Electroactive Polymers: Intelligent Materials Systems*, 2nd ed.; Wallace, G. G., Teasdale, P. R., Spinks, G. M., Kane-Maguire, L. A. P., Eds.; CRC Press: Boca Raton, FL, 2002.
4. (a) Osada, Y.; Okuzaki, H.; Hori, H. *Nature* **1992**, *355*, 242. (b) Osada, Y.; Matsuda, A. *Nature* **1995**, *376*, 219.
5. Beebe, D. J.; Moore, J. S.; Bauer, J. M.; Yu, Q.; Liu, R. H.; Devadoss, C.; Jo, B. *Nature* **2000**, *404*, 588.
6. Sidorenko, A.; Krupenkin, T.; Taylor, A.; Fratzl, P.; Aizenberg, J. *Science* **2007**, *315*, 487.
7. Yoshida, R. *Adv. Mater.* **2010**, *22*, 3463.
8. *Handbook of Stimuli-Responsive Materials*; Marek, W. U., Eds.; Wiley-VCH: Weinheim, Germany, 2011.
9. *Responsive Polymer Materials: Design and Applications*; Minko, S., Eds.; Blackwell Pub.: Oxford, U.K., 2006.
10. Hashidzume, A.; Harada, A. Stimuli-Responsive Systems. In *Supramolecular Polymer Chemistry*, Harada, A., Eds.; Wiley-VCH: Weinhein, Germany, 2011; pp 231−268.
11. Haraguchi, K.; Takehisa, T. *Adv. Mater.* **2002**, *14*, 1120.
12. Huang, T.; Xu, H.; Jiao, K.; Zhu, L.; Brown, H. R.; Wang, H. *Adv. Mater.* **2007**, *19*, 1622.
13. Haque, M. A.; Kurokawa, T.; Kamita, G.; Gong, J. P. *Macromolecules* **2011**, *44*, 8916.
14. Sun, J.-Y.; Zhao, X.; Illeperuma, W. R. K.; Chaudhuri, O.; Oh, K. H.; Mooney, D. J.; Vlassak, J. J.; Suo, Z. *Nature* **2012**, *489*, 133.
15. Bergman, S. D.; Wudl, F. *J. Mater. Chem.* **2008**, *18*, 41.
16. Cordier, P.; Tournilhac, F.; Soulie-Ziakovic, C.; Leibler, L. S. *Nature* **2008**, *451*, 977.
17. Burattini, S.; Colquhoun, H. M.; Fox, J. D.; Friedmann, D.; Greenland, B. W.; Harries, P. J. F.; Hayes, W.; Mackay, M. E.; Rowan, S. J. *Chem. Commun.* **2009**, 6717.
18. Burattini, S.; Greenland, B. W.; Hayes, W.; Mackay, M. E.; Rowan, S. J.; Colquhoun, H. M. *Chem. Mater.* **2011**, *23*, 6.
19. Fox, J.; J. Wie, J.; B. Greenland, W.; Burattini, S.; Hayes, W.; Colquhoun, H. M.; Mackay, M. E.; Rowan, S. J. *J. Am. Chem. Soc.* **2012**, *134*, 5362.
20. Wang, Q.; Mynar, J. L.; Yoshida, M.; Lee, E.; Lee, M.; Okuro, K.; Kinbara, K.; Aida, T. *Nature* **2010**, *463*, 339.
21. Tuncaboylu, D. C.; Sari, M.; Oppermann, W.; Okay, O. *Macromolecules* **2011**, *44*, 4997.
22. Wojtecki, R. J.; Meador, M. A.; Rowan, S. J. *Nat. Mater.* **2011**, *10*, 14.
23. Burnworth, M.; Tang, L.; Kumpfer, J. R.; Duncan, A. J.; Beyer, F. L.; Fiore, G. L.; Rowan, S. J.; Weder, C. *Nature* **2011**, *472*, 334.
24. Greef, T. F. A. D.; Smulders, M. M. J.; Wolffs, M.; Schenning, A. P. H. J.; Sijbesma, R. P.; Meijer, E. W. *Chem. Rev.* **2009**, *109*, 5687.
25. Wu, D. Q.; Wang, T.; Lu, B.; Xu, X. D.; Cheng, S. X.; Jiang, X. J.; Zhang, X.

Z.; Zhuo, R. X. *Langmuir* **2008**, *24*, 10306.
26. Koopmans, C.; Ritter, H. *Macromolecules* **2008**, *41*, 7418.
27. Liao, X.; Chen, G.; Jianga, M. *Polym. Chem.* **2013**, *4*, 1733.
28. Appel, E. A.; Loh, X. J.; Jones, S. T.; Biedermann, F.; Dreiss, C. A.; Scherman, O. A. *J. Am. Chem. Soc.* **2012**, *134*, 11767.
29. Appel, E. A.; del Barrio, J.; Loh, X. J.; Scherman, O. A. *Chem. Soc. Rev.* **2012**, *41*, 6195.
30. Miyauchi, M.; Harada, A. *J. Am. Chem. Soc.* **2004**, *126* (37), 11418.
31. Miyauchi, M.; Hoshino, T.; Yamaguchi, H.; Kamitori, S.; Harada, A. *J. Am. Chem. Soc.* **2005**, *127* (7), 2034.
32. Miyauchi, M.; Takashima, Y.; Yamaguchi, H.; Harada, A. *J. Am. Chem. Soc.* **2005**, *127* (9), 2984.
33. Tomimasu, N.; Kanaya, A.; Takashima, Y.; Yamaguchi, H.; Harada, A. *J. Am. Chem. Soc.* **2009**, *131*, 12339.
34. (a) Takashima, Y.; Nakayama, T.; Miyauchi, M.; Kawaguchi, Y.; Yamaguchi, H.; Harada, A. *Chem. Lett.* **2004**, *33*, 890. (b) Tamesue, S.; Takashima, Y.; Yamaguchi, H.; Shinkai, S.; Harada, A. *Angew. Chem., Int. Ed.* **2010**, *49*, 7461.
35. Takashima, Y.; Hatanaka, S.; Otsubo, M.; Nakahata, M.; Kakuta, T.; Hashidzume, A.; Yamaguchi, H.; Harada, A. *Nat. Commun.* **2012**, *3*, 1270.
36. Nakahata, M.; Takashima, Y.; Yamaguchi, H.; Harada, A. *Nat. Commun.* **2011**, *2*, 511.
37. Nakahata, M.; Takashima, Y.; Hashidzume, H.; Harada, A. *Angew. Chem. Int. Ed* **2013**, *52*, 5731.
38. Rekharsky, M. V.; Inoue, Y. *Chem. Rev.* **1998**, *98*, 1875.
39. Harada, A.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Yamaguchi, H. *Nat. Chem.* **2011**, *3*, 34.

Chapter 4

Adhesion between Plastics Containing Cyclodextrins and Adamantane based on Host–Guest Interactions

4-1. Introduction

Adhesives, which have a long history as glue and bonding agents, are a fundamental part of everyday life. Recently, adhesion phenomena have been related to many scientific and technological fields, and as polymer chemistry advances, adhesive materials are shifting toward intelligent polymeric adhesives[1-7]. In general, after a polymeric solid material is fractured, its fragments cannot be restored to the original solid state. Adhesion between fractured materials requires suitable bonds and primer reagents. On the other hand, a polymeric solid material possessing selective adhesion abilities would eliminate the need for bonds and primer reagents. Macroscopic self-assembled materials through non-covalent interactions have the potential to create a new paradigm in adhesion science, such as reversible adhesives[8-10] and self-healing materials[11-22].

Previously, macroscopic self-assemblies between soft materials have been achieved through macroscopic interactions (e.g., electrostatic interactions[23-26], capillary effects, etc.[27-29]). Recently, A. Harada et al. realized selective macroscopic self-assemblies through molecular interactions (i.e., hydrophobic interactions) using supramolecular hydrogels possessing host or guest polymers. Pieces of host and guest gels, which are chemically crosslinked acrylamide-based gels with either cyclodextrins (CDs) or small hydrocarbon moieties, adhere to one another via mutual molecular recognition of the CDs and the hydrocarbon groups on their surfaces[30]. External stimuli (e.g., light[31a], chemicals[31b], temperature[31c], and pH stimuli[31d]) reversibly control adhesion and cleavage between hydrogel

pieces in a macroscopic self-assembly system through host–guest interactions. Moreover, the author synthesized supramolecular self-healable materials crosslinked between poly(acrylamide) chains with inclusion complexes; these materials exhibit selective adhesion between cleaved surfaces and recover the material strength[32]. These studies suggest that host and guest molecules function as glue on the molecular level to achieve macroscopic properties. Although the molecular motion may be restricted on semi-hard surfaces, similar to the interface of soft materials, two semi-hard materials should adhere with host and guest molecules with complementary interactions.

Adhesion science through noncovalent interactions on the microscopic scale is particularly interesting because it creates new paradigm of supramolecular materials. Herein the author demonstrates the adhesion mechanism between semi-hard materials interfaces via host–guest interactions. Additionally, the author creates semi-hard materials having the recovery potentials and material strengths.

4-2. Experimental Section

Materials. β-Cyclodextrin (βCD) was obtained from Junsei Chemical Co., Ltd. Sodium hydride, ammonium peroxodisulfate, [2-(dimethylamino)ethyl]dimethylamine (TEMED), and sodium hydrogen carbonate ($NaHCO_3$) were obtained from Nacalai Tesque Inc. 1-Adamantanamine hydrochloride, acryloyl chloride was obtained from Tokyo Kasei Inc. DMSO-d_6 was obtained from Merck & Co., Inc. A highly porous synthetic resin (DIAION HP-20) used for column chromatography was purchased from Mitsubishi Chemical Co., Ltd. Water was purified with a Milli Q system. All of reagents were used without purification.

Measurements.

NMR spectrometer. One dimensional NMR spectra were recorded with a JEOL ECA-500 NMR spectrometer at 30 ^{o}C. Chemical shifts were referenced to the solvent values (δ = 2.49 ppm for DMSO-d_6).

Mass spectrometry. Positive-ion matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS) experiments were performed using a Bruker autoflex speed mass spectrometer using 2,5-dihydroxy-benzoic acid as a matrix. Mass number was calibrated by four peptides, i.e., angiotensin II ([M+H]+ 1046.5418), angiotensin I ([M+H]+ 1296.6848), substance P ([M+H]+ 1347.7354), and bombesin ([M+H]+1619.8223).

Ger permeation chromatography (GPC). GPC was performed in formamide (0.30 mL/min) using an TOSOH GPC-8020 Model II equipped with TOSOH TSKgel α-M column to determine molecular weights (M_n). M_n of host-guest gels were measured with respect to Poly(acrylamide) (PAAm) standards (American polymer standards Corp., Mentor, Ohio).

Tensile experiments. Mechanical properties of the gel were measured by the rupture testing system (Creep meter, RE-33005B, Yamaden Ltd.) in condition that tensile velocity is 0.1 mm /s.

Preparation of β-cyclodextrin acrylamide as a host monomer (AAm-βCD).[30] 6-Amino-βCD (5.0 g, 4.4 mmol) was dissolved in 200 mL of $NaHCO_3$ aq. (1.9 g, 2.2×10^1 mmol), and the pH of the solution was adjusted to approximately 10 with NaOH. Acryloyl chloride (7.2×10^2 μL, 8.8 mmol) was added to a solution of 6-amino-βCD in an ice bath. After stirring for five hours in an ice bath, the solution was evaporated to 30% of the total volume and poured into acetone (1 L). The precipitate was collected by suction filtration and dried in a vacuum oven (40 °C) overnight. The crude product was purified by reverse phase chromatography using HP-20 polystyrene gel (methanol/water) to give AAm-βCD (1.6 g, 31%). ^{1}H NMR (500 MHz, DMSO-d_6): δ 7.90 (t, 1H, amide), 6.26 (dd, 1H, olefin), 6.04 (dd, 1H, olefin), 5.49-5.82 (d, 1H, olefin and m, 14H, $O_{2,3}H$ of CD), 4.84 (m, 7H, C_1H of CD), 4.42 (m, 6H, O_6H of CD), 3.43-3.11 (m, 28H, $C_{2,3,4,5}H$ of CD, overlaps with HOD). MALDI-TOF MS; m/z = 1210.39 ($[C_{45}H_{73}NO_{35} + Na]^+$ = 1210.28, 0.009% error).

Preparation of *N*-adamantan-1-yl acrylamide as a guest monomer (AAm-Ad)[30]**.** 1-Adamantanamine hydrochloride (5.0 g, 0.27 mmol) and triethylamine (7.8 mL, 0.56 mmol) were dissolved in 200 mL of THF in an ice bath. Acryloyl chloride (2.8 mL, 0.29 mmol) was added dropwise into the solution in an ice bath. The solution was stirred for two days in an ice bath, and was subsequently warmed to room temperature while stirring. The reacted solution was evaporated, and the solid was dissolved in 100 mL of chloroform. The solution was washed with water to remove the salt. The organic layer was adsorbed to silica and purified by silica gel column chromatography (eluted with hexane/ethyl acetate = 50/50 vol%), yielding 2.9 g of the desired product. Yield: 52%. ^{1}H NMR (500 MHz, ($CDCl_3$): δ 6.21 (dd, 1H, olefin), 6.01 (dd, 1H, olefin), 5.56 (dd, 1H, olefin), 5.22 (brs, 1H, NH), 2.06 (m, 9H, adamantane), 1.68 (m, 6H, adamantane). MALDI-TOF MS ; m/z = 228.6 ($[C_{13}H_{19}NO+Na]^+$ = 228.9, 0.13% error).

Preparation of βCD Plastics(*x*) (βCD P(*x*)). The βCD P(10) was prepared by copolymerization of acrylamide (88 mol%), AAm-βCD (10 mol%) and MBAAm (2 mol%) by radical polymerization initiated by APS (0.5 mol%) and TEMED (0.5 mol%) in water (2 M). After polymerization, the βCD P(10) was obtained by drying up to remove absorbed water as following section of drying process of βCD P(x), Ad P(x) and AAm P(2).

Preparation of Ad Plastics(*x*) (Ad P(*y*)). The Ad P(5) was prepared by copolymerization of acrylamide (93 mol%), AAm-Ad (5 mol%) and MBAAm (2 mol%) by radical polymerization initiated by AIBN (0.5 mol%) in DMSO (2 M). After polymerization, the Ad P(5) was obtained by drying up to remove absorbed water as following section of drying process of βCD P(x), Ad P(x) and AAm P(2).

Preparation of AAm Plastics(2) (Ad P(2)). The AAm P(2) was prepared by copolymerization of acrylamide (98 mol%) and MBAAm (2 mol%) by radical polymerization initiated by APS (0.5 mol%) and TEMED (0.5 mol%) in water (2 M). After polymerization, the AAm P(10) was obtained by drying up to remove absorbed water as following section of drying process of βCD P(x), Ad P(x) and AAm P(2).

Preparation of βCD polymer. The βCD polymer was prepared by copolymerization of acrylamide (95 mol%) and AAm-βCD (5 mol%) by radical polymerization initiated by AIBN (0.5 mol%) in DMSO (2 M). After polymerization, the solution of the βCD polymer was purified by reprecipitation with methanol. White powder was got by drying up in vacuo after filtration.

Preparation of Ad polymer. The Ad polymer was prepared by copolymerization of acrylamide (99 mol%) and AAm-Ad (1 mol%) by radical polymerization initiated by

AIBN (0.5 mol%) in DMSO (2 M). After polymerization, the solution of the Ad polymer was purified by reprecipitation with methanol. White powder was got by drying up in vacuum oven after filtration.

Preparation of AAm polymer. The AAm polymer was prepared by copolymerization of acrylamide by radical polymerization initiated by APS (0.5 mol%) and TEMED (0.5 mol%) in water (2 M). After polymerization, the solution of the AAm polymer was purified by reprecipitation with methanol. White powder was got by drying up in vacuo after filtration.

4-3. Results and discussion

4-3-1. Preparation of dried materials

To achieve adhesion through host–guest interactions between host and guest plastics, hard materials containing β-cyclodextrin (βCD) and adamantane (Ad) were prepared because βCD is the relatively high affinity for Ad ($K_a = 10^4$ M^{-1}) [33]. Figure 4-1 depicts the chemical structures of βCD plastics (βCD P), Ad plastics (Ad P), βCD-Ad plastics (βCD-Ad P), and acrylamide plastics (AAm P). βCD P was prepared by polymerization of βCD acrylamide (AAm-βCD), acrylamide (AAm), and *N*,*N*′-methylenebis(acrylamide) (MBAAm) in water. After polymerization, βCD P(*x*) was obtained by drying to remove absorbed water under atmospheric pressure for two days, and subsequently at 27 °C in vacuo for a day (Figure 4-2). Ad P(*x*) was obtained by polymerizing a mixture of AAm-Ad, AAm, MBAAm, and 2,2'-azobis(2-methylpropionitrile) (AIBN) in dimethylsulfoxide (DMSO) because *N*-adamantan-1-yl acrylamide (AAm-Ad) was insoluble in water. After polymerization, Ad P(*y*) was obtained by washing in water several times followed by drying under the same conditions as βCD P(*x*). *x* and *y* represent the mol% of the βCD and Ad units, respectively. Additionally, to obtain the self-healing hard materials, βCD-Ad gel(*x*, *y*) contained both βCD and Ad on the chain was prepared as previously reported[26]. The polymer chains inside βCD-Ad gel(*x*, *y*) was cross-linked only by inclusion complex formation between βCD and Ad units. Afterwards, βCD-Ad P(*x*, *y*) was obtained by drying under the same conditions as βCD P(*x*). AAm P(*z*), which served as the control material, was prepared in same manner as βCD P(*x*). *z* is defined as the mol% of MBAAm crosslinking the molecules.

The author prepared the βCD polymer, Ad polymer, and AAm polymer as model polymers without crosslinking units to determine the molecular weight of plastic prepared under the same conditions for each plastic. According to the GPC results, all of the polymers showed similar molecular weights ($M_n = 6.0 \times 10^4$). The introduced host and guest

units into the polymers were determined to be a planned molar ratio using ^{1}H NMR spectroscopy.

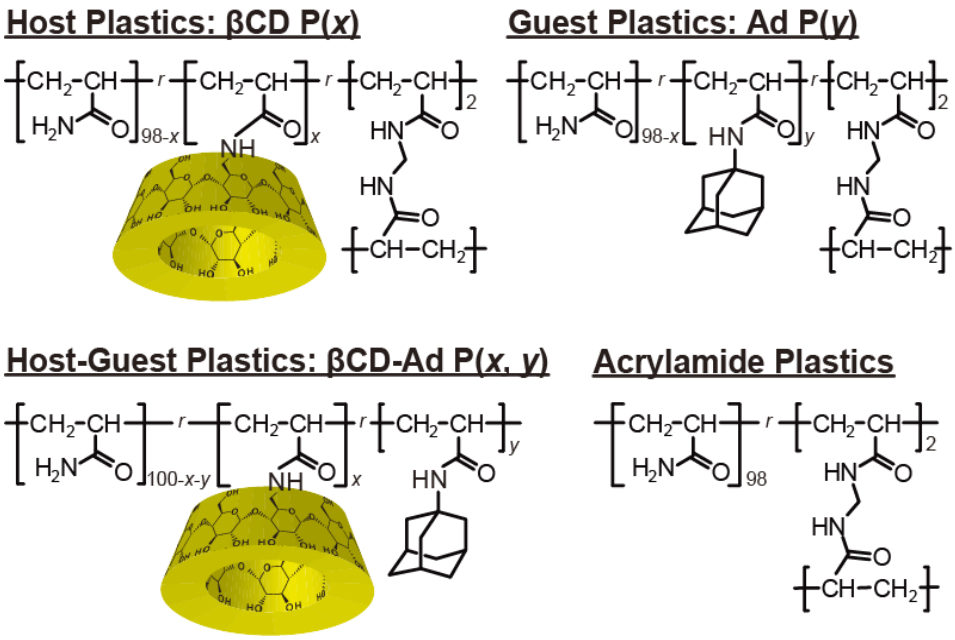


Figure 4-1. Chemical structures of βCD P(x), Ad P(y), βCD-Ad P(x, y), and AAm P(2). x and y represent the feed ratios of the host and guest molecules, respectively. AAm P(2) has two mol% of MBAAm as a cross-linking unit.

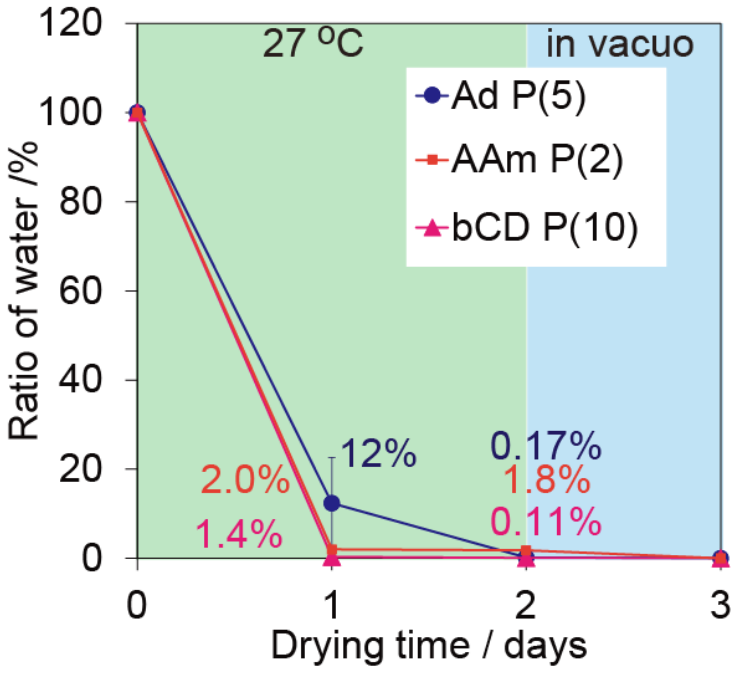


Figure 4-2. Characterization of water content ratio as a function of drying time.

4-3-2. Adhesion behavior between βCD P(*x*) and Ad P(*x*)

To confirm the adhesive strength between βCD P(10) and Ad P(5), a dumbbell (1 kg) was dangled on the end of a piece of string attached to bonded plastics composed of βCD P(10)/Ad P(5). Figure 4-3a shows the procedure to attach the dumbbell and lifting the dumbell. First, water (2 μL) was added onto the Ad P(5) surface. Then the wet Ad P(5) was attached to βCD P(10). Next, the attached material (βCD P(10)/Ad P(5)) was dried using a dryer for 5 min. Prior to lifting the dumbbell, the dumbbell was connected to the βCD P(5) side of the adherent sample βCD P(10)/Ad P(5) using clip via a pulley. The Ad P(10) side of the βCD P(10)/Ad P(5) was also held via a clip. Finally, the author hoisted the dumbbell with βCD P(10)/Ad P(5). When the Ad P(5) side of the βCD P(10)/Ad P(5) was pulled, the 1 kg dumbbell was suspended 150 mm above the ground (Figure 4-3b). These results suggest that the adhesive strength of βCD P(10)/Ad P(5) is sufficiently strong to withstand a 1 kg weight.

The adhesive strength between βCD P(*x*) and Ad P(*y*) were analyzed by tensile experiments (Figure 4-3c). Ad P(*y*) was attached to βCD P(*x*) after adding water (2 μL) onto a surface of Ad P(*y*). After drying for 24 h, the adhesive strength of βCD P(*x*)/Ad P(*y*) was estimated using a creep meter at 1 mm/s of the tensile velocity under a sample size of 3 × 3 × 10 mm^3. Figure 4-3d shows the adhesive strength between βCD P(*x*) and Ad P(3 and 5). Identical species between βCD P(*x*)s or between Ad P(*y*)s that were connected to each other did not show adhesion, whereas heterogeneous connections between βCD P(*x*) and Ad P(*y*) adhered each other. The adhesive strength of βCD P(*x*)/Ad P(3 and 5) increased as a function of *x* in the feed ratio of βCD. Similarly, the adhesion strength βCD P(1, 3, 5 and 10)/Ad P(*y*) increased as the feed ratio (*y*) of the Ad molecule inside Ad P(*y*) increased. The combination between βCD P(10) and Ad P(5) showed the highest adhesive strength (5.1 MPa). These results indicate that the host–guest interaction on the adhesion surface affects the adhesive strength.

On the other hand, Figure 4-3e showed the stress-strain curves with/without aqueous solutions of competitive molecules (βCD and 1-adamantane carboxylic acid sodium salt (AdCANa)) to the interface between βCD P(10) and Ad P(5). The adhesive strength (5.1 MPa) between βCD P(10) and Ad P(5) decreased when added the competitive molecules. Moreover, the adhesive strength of βCD P(10)/Ad P(5) decreased as the concentration of competitive molecules increased. The addition of βCD or AdCANa as competitive molecules inhibited the formation of the inclusion complexes between the βCD and Ad units on the interface because competitive molecules covered the free host and guest molecules on the surface. The measured adhesive strength of βCD P(*x*)/AAm P(2), Ad P(*y*)/AAm P(2), and AAm P(2)/AAm P(2) showed very weak stress values, which were one-tenth of the original stress of βCD P(10)/Ad P(5) Because AAm P(2) did not possess both host and guest molecules, βCD P(*x*)/AAm P(2), Ad P(*y*)/AAm P(2), and AAm P(2)/AAm P(2) lacked an adhesive ability through host–guest interactions. These results indicate that host–guest interactions at the interface result in the strong adhesive strength between βCD P(*x*) and Ad P(*y*).

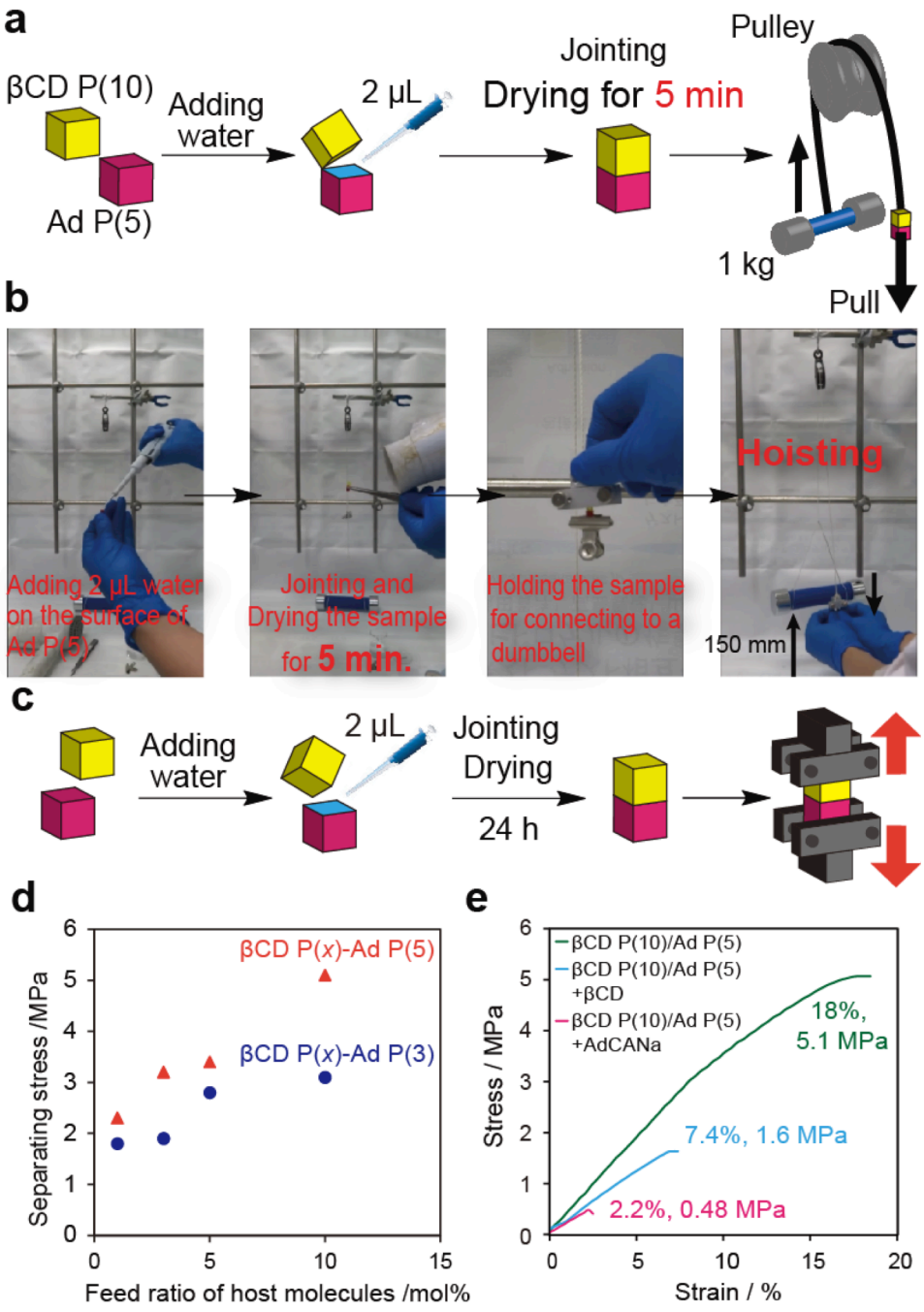


Figure 4-3. Estimation of the adhesive strengths. (a) Procedure for the hoisting experiments. (b) Images of the hoisting experiments. Water (2 μL) was added to Ad P(5) on an adhesive surface. Afterwards, Ad P(5) and βCD P(10) were joined. Jointed material was dried for 5 min before a hole was created. Then a 1 kg dumbbell was hoisted. (c) Experimental procedure to estimate adhesive strengths. (d) Dependence of the feed ratio of the host molecules on adhesive strength. (e) Stress–strain curves of the competitive

4-3-3. Microscopic observations of adhesive surfaces.

To investigate the adhesive behavior on the interface, changes in the adhesion surface of βCD P(10)/Ad P(5) were observed via optical microscopy. The start time (0 min) was defined when water (2 μL) was added. Figure 4-4a shows the adhesive interfaces of βCD P(10)/Ad P(5) for two different magnifications (× 4 and × 10). βCD P(10)/Ad P(5) showed a gap at the initial state (0 min), which was the separated state. After 60 min, βCD P(10) and Ad P(5) adhered on the interface. The adhesive interface of βCD P(10)/Ad P(5) maintained the adhered state after standing for a day. Moreover, when observing at a large magnification (× 10), the separated interface of the βCD P(10)/Ad P(5) adhered after 15 min, and after 20 min, both surfaces of βCD P(10) and Ad P(5) were pulled together like a pair of magnets. After 60 min, the interface of βCD P(10)/Ad P(5) adhered and filled the gap.

However, the gaps of βCD P(10)/AAm P(2), Ad P(5)/AAm P(2), and AAm P(2)/AAmP(2) did not change at the contact interfaces. After standing for 60 min, these combinations separated (Figure 4-4b). Host–guest interactions did not perform in the contact interfaces of βCD P(10)/AAm P(2), Ad P(5)/AAm P(2), and AAm P(2)/AAmP(2) because AAm P(2) lacked host and guest molecules.

Figure 4-4c schematically illustrates the adhesive mechanism between βCD P(10) and Ad P(5). The host and guest molecules on the surface formed inclusion complexes upon touching each other. These inclusion complexes then pulled the polymer chain from the host and guest plastics to form more inclusion complexes. Thus, each polymer chain intruded into the interface of the plastics. These results indicate that the host–guest interactions on the interface achieve the adhesion between hard materials.

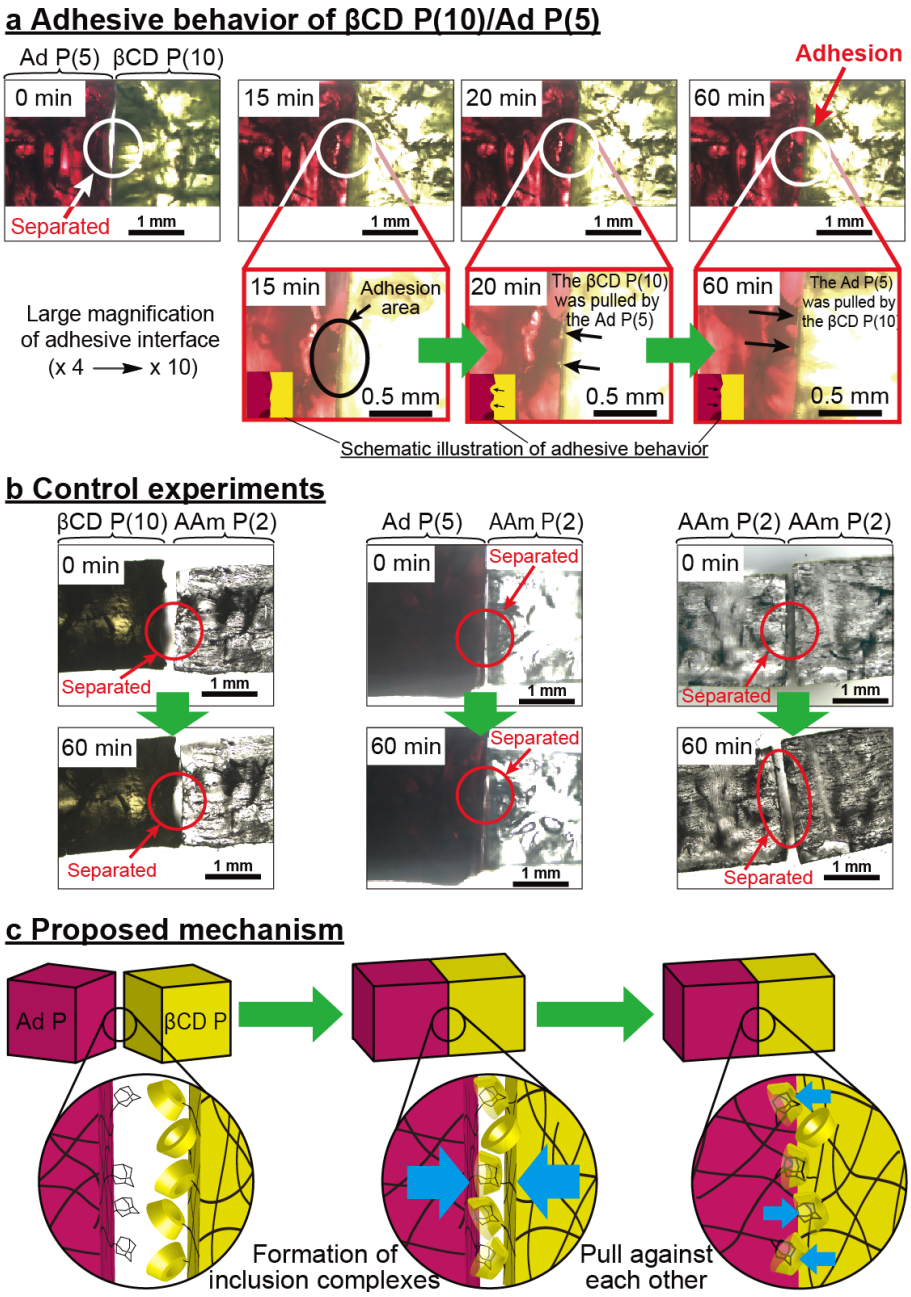


Figure 4-4. Images of the adhesive interface. (a) Surface of βCD P(10)/Ad P(5) is in the separated state before adding water. After 60 min, the interface of βCD P(10)/Ad P(5) shows an adhesive state. Moreover, a large magnification of the adhesive area demonstrates that βCD P(10) and Ad P(5) pull toward each other. (b) Surfaces of βCD P(10)/AAm P(2), Ad P(5)/AAm P(2), and AAm P(2)/AAm P(2) show separated states after standing for 60 min. (c) Schematic illustration of the adhesion mechanism. First, the free Ad units of Ad P(*y*) form inclusion complexes with the free βCD units of βCD P(*x*). Second, βCD P(*x*) and Ad P(*y*) pull the polymer chains toward each other. Finally, inclusion complexes, free Ad molecules, free βCD molecules, and main chain polymers intrude into the adhesive interfaces of βCD P(10)/Ad P(5).

4-3-4. Self-healing of hard materials.

Figure 4-5a shows the procedure for the self-healing experiments of βCD-Ad P(*x*, *y*). To investigate the self-healing ratio of βCD-Ad P(0.3, 0.4) at various rejoining times, the material strength and separating stress were analyzed by tensile tests. First, the initial tensile rupture stress ($S_{initial}$) of βCD-Ad P(0.3, 0.4) (size: 2 × 2 × 5 mm^3) was measured by a 0.1 mm/s tensile velocity. After fracturing βCD-Ad P(0.3, 0.4) to give two pieces, water (2 μL) was dropped onto a fractured surface. The ruptured βCD-Ad P(0.3, 0.4) was allowed to rejoin for a prescribed time (*n* h). After reattaching the fracture surfaces of βCD-Ad P(0.3, 0.4) for a prescribed time (*n* h), the recovery rupture stress (S_n) was determined by the tensile test. The recovery ratio (R_n) is calculated by a following equation, $R_n = S_n / S_{initial} \times 100$.

Figure 4-5b shows images of an adhesion surface as a function of time. The optical microscope showed a self-healing behavior on the rejoined interfaces of βCD-Ad P(0.3, 0.4). The start time (0 min) was defined as the time when the fractured pieces were rejoined after water (2 μL) was dropped on the fractured surface. After 60 min, the gap of the fractured βCD-Ad P(0.3, 0.4) was spontaneously filled. The rejoined βCD-Ad P(0.3, 0.4) was not separated by picking up the sample with tweezers. However, βCD-Ad P(0.3, 0.4) did not mend when an AdCANa aqueous solution was dropped on the fractured surface, indicating that the self-healing behavior of βCD-Ad P(0.3, 0.4) was due to host–guest interactions between βCD and Ad units.

Figure 4-5c shows the stress–strain curves of the initial tensile rupture (blue line: $S_{initial}$) and recovery tensile rupture after reattaching for 48 h (pink line: S_{48}). Both stress–strain curves pursued the same line until fracturing. After reattaching for 48 h, the material strength recovered to be the recovery stress ratio (R_{48}) = 88%, which was calculated using $S_{initial}$ and S_{48}. Figure 4-5d shows R_n of the βCD-Ad P(0.3, 0.4) as a function of time. After an hour, R_1 exceeded 40%, which is a relatively fast recovery property. Moreover, R_n increased as the rejoining time increased, and R_{48} = 88%. On the other hand, when the

fractured surface of βCD-Ad P(0.3, 0.4) was touched at a non-fractured surface, these samples did not mend, even after 24 h. The free host and guest molecules, which appeared by a rupture on the surface of the βCD-Ad P(*x*, *y*), play important roles in the self-healing ability on an adhesive interface.

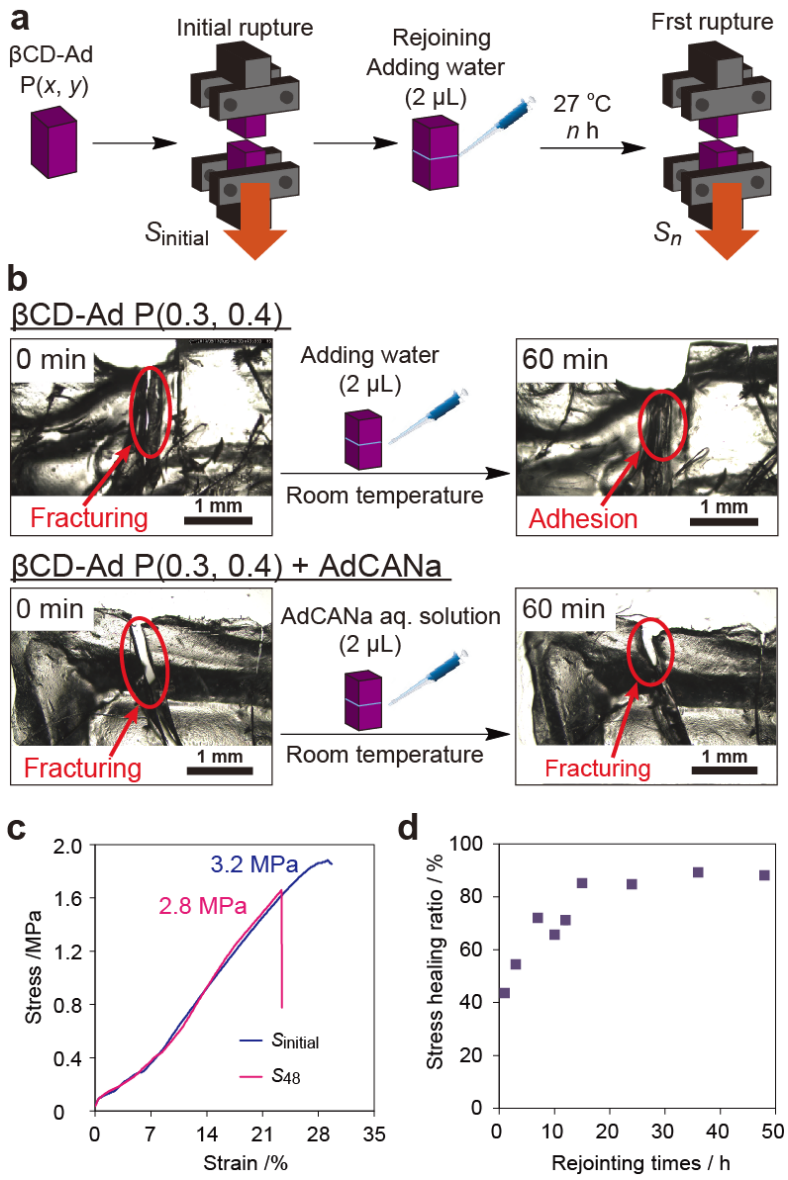


Figure 4-5. Adhesion behavior of cut βCD-Ad P(0.3, 0.4). (a) Schematic illustration of the tensile test to measure the rupture stress and stress healing ratio. (b) Microscopic images of adhesive surfaces. Cut pieces of βCD-Ad P(*m*, *n*) show an adhesive behavior upon adding water (2 μL). However, adding AdCANa aqueous solution inhibited the adhesion between cut pieces of βCD-Ad P(*m*, *n*). (c) Stress–strain curves of the initial tensile rupture (blue line: $S_{initial}$) and the recovery tensile rupture after reattaching for 48 h (pink line: S_{48}). (d) Stress healing ratio of a function of rejoining time.

The author also investigated the durability of adhesions in βCD-Ad P(0.3, 0.4) (Figure 4-6). R_{cm} shows the recovery ratio and m is cycle times. βCD-Ad P(0.3, 0.4) showed a high R_{cm} even after three cycles (R_{c3} = 60%). After the fourth cycle, the mended βCD-Ad P(0.3, 0.4) ruptured not at the rejoined surface but at another location, this fracturing might be due to the accumulated load. These results suggest that βCD-Ad P(0.3, 0.4) has high self-healing properties even in hard materials.

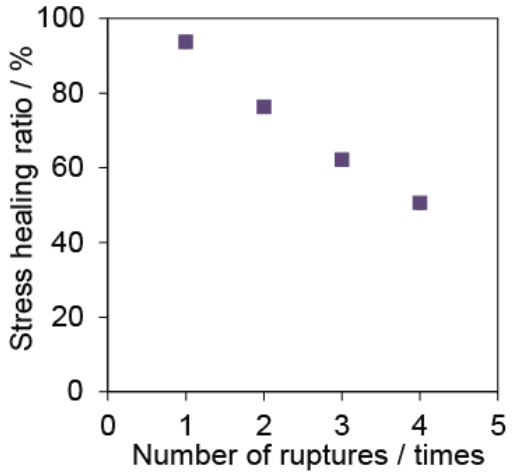


Figure 4-6. Stress healing ratio of the βCD-Ad P(0.3, 0.4) of each cycle times.

4-4. Conclusion

The author successfully created self-adhesive materials, which exhibit strong adhesive ability through host–guest interactions using β-cyclodextrin as a host molecule and adamantane as a guest molecule. The adhesive strength between plastics containing β-cyclodextrin (βCD P(*x*)) or adamantane (Ad P(*y*)) is greatly influenced by adding competitive molecules and the molar ratio of the βCD and Ad units, suggesting that the host–guest interactions between βCD and Ad units fulfill an important role in the adhesion between βCD P(*x*) and Ad P(*y*). Although the author hypothesized that semi-hard materials would adhere weakly or not at all, βCD P(*x*) and Ad P(*y*) show a robust adhesive strength even if the molecular mobility on the surface is decreased. Thus, the host–guest interactions at the interface may be responsible for the strong binding. In addition, the author created a self-healable material constructed by inclusion complexes of βCD and Ad (βCD-Ad P(0.3, 0.4)), which show a relatively high stress healing ratio (88%) and high adhesive strength (2.8 MPa). These results suggest that β-cyclodextrin and adamantane function as glue on the molecular scale to achieve macroscopic adhesion. The author believes that this adhesive mechanism will provide insight into other adhesion mechanisms.

REFERENCES

1. Boeder, C. W. Chapter 5. In *Structural Adhesives Chemistry and Technology,* Hartshorn, S. R., Eds.; Plenum press: New York, 1986; pp 217–247.
2. Rich, R. D. *Handbook of Adhesive Technology*, Pizzi, A.; Mittal, K.; Eds.; Marcel Dekker, Inc.: New York, 1994.
3. Pocius, A. V. *Adhesion and Adhesives Technology*, Hanser: Munich, 2002.
4. Kamino, K. *Biological Adhesives*, Smith, A. M.; Callow, J. A.; Eds.; Springer: Heidelberg, 2006, pp 145–166.
5. Petrie, E. M. *Handbook of Adhesives and Sealants*, McGraw-Hill: Chicago, 2007.
6. Brockmann, W.; Geiß, P. L.; Klingen, J.; Schröder, B. *Adhesive Bonding*, Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, 2009.
7. Onusseit, H.; Wefringhaus, R.; Dreezen, G.; Wichelhaus, J.; Schall, J.; Thiele, L.; Halteren, A. 1. General" in Ullmann's Encyclopedia of Industrial Chemistry. *Adhesives,* Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, 2010.
8. Carre, A.; Schultz, J. *The Journal of Adhesion* **1984**, *17*(2), 135.
9. Anderson, C. A.; Jones, A. R.; Briggs, E. M.; Novitsky, E. J.; Kuykendall, D. W.; Scottos, N. R.; Zimmerman, S. C. *J. Am. Chem. Soc.* **2013**, *135*(19), 7288.
10. Kobayashi, M.; Takahara, A. *Polym. Chem.* **2013**, *4*, 4987.
11. Dry, C. M. Smart Building Materials Which Prevent Damage and Repair Themselves. In *Smart Materials Fabrication and Materials for Micro-Electro-Mechanical Systems*, Symposium held April 28–30, 1992, San Francisco, CA, vol. 276 in series Materials Research Society Proceedings, MRS Philadelphia: PA, 331, 1992.
12. Bergman, S. D.; Wudl, F. *J. Mater. Chem.* **2008**, *18*, 41.
13. Wool, R. P. *Soft Matter* **2008**, *4*, 400.
14. Urban, M. W. *Prog. Polym. Sci.* **2009**, *34*, 679.
15. Burattini, S.; Greenland, B. W.; Chappell, D.; Colquhoun, H. M.; Hayes, W. *Chem. Soc. Rev.* **2010**, *39*, 1973.
16. Hager, M. D.; Greil, P.; Leyens, C.; van der Zwaag, S.; Schubert, U. S. *Adv. Mater.* **2010**, *22*, 5424.
17. Syrett, J. A.; Becer, C. R.; Haddleton, D. M. *Polym. Chem.* **2010**, *1*, 978.
18. *Handbook of Stimuli-Responsive Materials*; Urban, M. W., Eds.; Wiley-VCH: Verlag GmbH, 2011.
19. *Self-Healing Polymers*; Binder, W. H., Eds.; Wiley-VCH: Verlag GmbH, 2013.
20. White, S. R.; Sottos, N. R.; Geubelle, P. H.; Moore, J. S.; Kessler, M. R.; Sriram, S R.; Brown, E. N.; Viswanathan, S. *Nature* **2001**, *409*, 794.
21. Chen, X. X.; Dam, M. A.; Ono, K.; Mal, A.; Shen, H. B.; Nut, S. R.; Sheran, K.; Wudl, F. *Science* **2002**, *295*, 1698.
22. Ling, J.; Rong, M.; Zhang, M. *Polymer* **2012**, *53*, 2691.
23. Grzybowski, B. A.; Jiang, X.; Stone, H. A.; Whitesides, G. M. *Phys. Rev. E* **2001**, *64*, 011603.
24. Whitesides, G. M.; Grzybowski, B. *Science* **2002**, *295*, 2418.
25. Boncheva, M.; Andreev, S. A.; Mahadevan, L.; Winkleman, A.; Reichman, D. R.; Prentiss, M. G.; Whitesides, S.; Whitesides, G. M. *Proc. Natl Acad. Sci. USA* **2005**, *102*, 3924.
26. Mirica, K. A.; Ilievski, F.; Ellerbee, A. K.; Shevkoplyas, S. S.; Whitesides, G.

M. *Adv. Mater.* **2011**, *23*, 4134.
27. Bowden, N.; Terfort, A.; Carbeck, J.; Whitesides, G. M. *Science* **1997**, *276*, 233.
28. Bowden, N. B.; Weck, M.; Choi, I. S.; Whitesides, G. M. *Acc. Chem. Res.* **2001**, *34*, 231.
29. Wolfe, D. B.; Snead, A.; Mao, C.; Bowden, N. B.; Whitesides, G. M. *Langumuir* **2003**, *19*, 2206.
30. Harada, A.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Yamaguchi, H. *Nature Chemistry* **2011**, *3*, 34.
31. a) Yamaguchi, H.; Kobayashi, Y.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Harada, A. *Nat. Commun.* **2012**, *3*, 603. b) Zheng, Y.; Hashidzume, A.; Takashima, Y.; Yamaguchi, H.; Harada, A. *Nat. Commun.* **2012**, *3*, 831. c) Zheng, Y.; Hashidzume, A.; Takashima, Y.; Yamaguchi, H.; Harada, A. *ACS Macro Lett.* **2012**, *1*, 1083. d) Zheng, Y.; Hashidzume, A.; Harada, A. *Macromol. Rapid Commun.* **2013**, *34*, 1062.
32. Kakuta, T.; Takashima, Y.; Nakahata, M.; Otsubo, M.; Yamaguchi, H.; Harada, A., *Adv. Mat.*, **2013**, *25*, 2849.
33. Rekharsky, M. V.; Inoue, Y. *Chem. Rev.* **1998** *98*, 1875.

Chapter 5

High-Functional Supramolecular Materials using Star-Shaped Polymer Terminal Modified Guest Molecules and Cyclodextrins

5-1. Introduction

In the previous chapter, the author successfully prepared self-healing materials in wet and semi-wet condition by using cyclodextrin and alkly compounds. Additionally, in the chapter 3, the material which was called βCD-Ad gel(0.3, 0.4) exhibited highly elastic properties. The author hypotheses supramolecular materials, prepared by polymerization of inclusion complexes using star-shaped polymer in water, have high functional properties, i.e., self-healing[1-9] and shape memory[10-14]. The flexibility and uniformity between cross-linked units is related with mechanical and functional properties. Recently, uniformity structure inside the gel produced strong mechanical properties[15]. The structure of this gel showed uniformed three-dimensional network by Small-Angle Neutron Scattering[16].

Herein, the author demonstrates the mechanical and functional properties of the supramolecular hydrogel cross-linked inclusion complexes using β-cyclodextrin and terminal-guest-modified star-shape poly(ethyleneglycol) via host-guest interactions. Additonally, the author created hard materials and estimated the mechanicalproperties.

5-2. Experimental Section

General Procedures. β-Cyclodextrin (βCD) was obtained from Junsei Chemical Co., Ltd. Sodium hydrogen carbonate ($NaHCO_3$), ammonium peroxodisulfate (APS), 1-adamantanamine, [2-(dimethylamino)ethyl]dimethylamine (TEMED), 1,2-ethylenediamine, triethylamine (Et_3N), *N*,*N*-diisopropylethylamine (DIPEA) and dichloromethane (DCM) were obtained from Nacalai Tesque Inc. TPE-100GS, TPE-150GS, TPE-400GS and HGEO-150GS were obtained from DDS Development Div., NOF CORPORATION. Dimethyl sulfoxide and acrylamide were obtained from Wako Pure Chemical Indust ries, Ltd. Acryloyl chloride was obtained from Tokyo Kasei Inc. DMSO-d_6 was obtained from Merck & Co., Inc. $CHCl_3$-*d* was obtained from Cambridge Isotope Laboratories, Inc. Spectra/Por dialysis Membrane (MWCO: 2,000) was obtained from Funakoshi Co., Ltd. A highly porous synthetic resin (DIAION HP-20) used for column chromatography was purchased from Mitsubishi Chemical Co., Ltd. Water, which was used to prepare the aqueous solutions (except for NMR measurements), was purified with a Millipore Elix 5 system. Other reagents were used as received.

Measurements. One dimensional NMR spectra were recorded with a JEOL ECA-500 NMR spectrometer at 30 ^{o}C. Chemical shifts were referenced to the solvent values (δ = 2.49 ppm for DMSO-d_6 and δ = 7.26 ppm for $CHCl_3$-*d*). Dynamic viscoelasticity were measured using an Anton Paar MCR302 rheometer at strain of 0.1%. Mechanical properties of the gel were measured by the rupture testing system (Creep meter, RE-33005B, Yamaden Ltd.). Ger permeation chromatography (GPC) was performed in formamide (0.30 mL/min) with 0.1% lithium bromide using a TOSOH GPC-8020 Model II equipped with TOSOH TSKgel α-M column to determine molecular weights (M_n). M_n of host-guest gels were measured with respect to polystyrene sulfonate Na salt (PSSNa) standards (American polymer standards Corp., Mentor, Ohio).

Preparation of Terminal-Adamanatane-Modified tera-Poly(ethylenglycol) 10k (TPAd10k). PTE-100GS (0.20 g, 1.8×10^{-5} mol) was dissolved in 15 mL of CH_2Cl_2. 1-aminoadamantane (0.54 g, 2.9×10^{-4} mol) and were dissolved in 5 mL of CH_2Cl_2. The CH_2Cl_2 mixed solution of PTE-100GS was added to the CH_2Cl_2 solution of 1-aminoadamantane. The solution was stirred for 3 days at room temperature. The solvent was evaporated and the solid was dissolved in DMSO. The compound was dialyzed by DMSO and water. The aqueous solution of the compounds was dried up by freezing dry and gave 0.16 g of the desired product. Yield: 81%. ^{1}H NMR (500 MHz, Chloroform-*d*): δ 5.33 (brs, 1H, NH), 3.60 (m, nH, CH_2 of PEG), 2.31 (t, 2H, CH_2 of terminal structure), 2.10 (t, 2H, CH_2 of terminal structure), 2.04 (brs, 9H, adamantane), 1.95 (m, 6H, adamantane), 1.89 (t, 2H, CH_2 of terminal structure). Anal. Calcd for $C_{578}H_{1120}N_4O_{268}(H_2O)_{27}$: C, 53.81; H, 9.17; N, 0.43. Found: C, 53.85; H, 8.87; N, 0.53 (0.30% error).

Preparation of Terminal-Adamanatane-Modified tera-Poly(ethylenglycol) 15k (TPAd15k). PTE-150GS (0.20 g, 1.3×10^{-5} mol) and *N*,*N*-diisopropylethylamine (10 μL, 5.8×10^{-5} mol) was dissolved in 10 mL of CH_2Cl_2. 1-aminoadamantane (0.31 g, 2.1×10^{-4} mol) was dissolved in 3 mL of CH_2Cl_2. CH_2Cl_2 solution of PTE-150GS was added to the CH_2Cl_2 solution of 1-aminoadamantane. The solution was stirred for 3 days at room temperature. The solvent was evaporated and the solid was dissolved in DMSO. The compound was dialyzed by DMSO and water. The aqueous solution of the compounds was dried up by freezing dry and gave 0.18 g of the desired product. Yield: 91%. ^{1}H NMR (500 MHz, Chloroform-*d*): δ 5.34 (brs, 1H, NH), 3.64 (m, nH, CH_2 of PEG), 2.39 (t, 2H, CH_2 of terminal structure), 2.13 (t, 2H, CH_2 of terminal structure), 2.07 (brs, 9H, adamantane), 1.99 (m, 6H, adamantane), 1.92 (t, 2H, CH_2 of terminal structure). Anal. Calcd for $C_{769}H_{1504}N_4O_{364}(H_2O)_8$: C, 55.06; H, 9.13; N, 0.33. Found: C, 54.85; H, 8.82; N, 0.41 (0.30% error).

Preparation of Terminal-Adamanatane-Modified tera-Poly(ethylenglycol) 40k (TPAd40k). PTE-400GS (0.20 g, 4.8×10^{-6} mol) and *N*,*N*-diisopropylethylamine (3.8 μL, 2.2×10^{-5} mol) were dissolved in 8 mL of CH_2Cl_2. 1-aminoadamantane (0.12 g, 7.7×10^{-5} mol) and were dissolved in 3 mL of CH_2Cl_2. The CH_2Cl_2 solution of PTE-400GS was added to the CH_2Cl_2 solution of 1-aminoadamantane. The mixed solution was stirred for 3 days at room temperature. The solvent was evaporated and the solid was dissolved in DMSO. The compound was dialyzed by DMSO and water. The aqueous solution of the compounds was dried up by freezing dry and gave 0.12 g of the desired product. Yield: 61%. ^{1}H NMR (500 MHz, Chloroform-*d*): δ 5.35 (brs, 1H, NH), 3.64 (m, nH, CH_2 of PEG), 2.39 (t, 2H, CH_2 of terminal structure), 2.14 (t, 2H, CH_2 of terminal structure), 2.06 (brs, 3H, adamantane), 1.99 (brs, 6H, adamantane), 1.93 (t, 2H, CH_2 of terminal structure), 1.64 (m, 6H, adamantane). Anal. Calcd for $C_{2049}H_{4064}N_4O_{1004}(H_2O)_{24}$: C, 54.38; H, 9.16; N, 0.12. Found: C, 54.38; H, 8.90; N, 0.15 (0.26% error).

Preparation of Terminal-Adamanatane-Modified octa-Poly(ethylenglycol) 15k (OPAd15k). HGEO-150GS (0.20 g, 1.2×10^{-5} mol) and *N*,*N*-diisopropylethylamine (17 μL, 9.9×10^{-5} mol) were dissolved in 15 mL of CH_2Cl_2. 1-aminoadamantane (0.12 g, 7.7×10^{-5} mol) and were dissolved in 5 mL of CH_2Cl_2. The CH_2Cl_2 solution of HGEO-150GS was added to the CH_2Cl_2 solution of 1-aminoadamantane. The mixed solution was stirred for 3 days at room temperature. The solvent was evaporated and the solid was dissolved in DMSO. The compound was dialyzed by DMSO and water. The aqueous solution of the compounds was dried up by freezing dry and gave 0.11 g of the desired product. Yield: 54%. ^{1}H NMR (500 MHz, Chloroform-*d*): δ 5.34 (brs, 1H, NH), 3.64 (m, nH, CH_2 of PEG), 2.39 (t, 2H, CH_2 of terminal structure), 2.14 (t, 2H, CH_2 of terminal structure), 2.06 (brs, 3H, adamantane), 1.99 (brs, 6H, adamantane), 1.93 (t, 2H, CH_2 of terminal structure), 1.67 (m, 6H, adamantane). Anal. Calcd for $C_{826}H_{1582}N_8O_{373}(H_2O)_{24}$: C, 55.03; H, 9.11; N, 0.62. Found: C, 55.03; H, 8.84; N, 0.56 (0.27% error).

5-3. Results and discussion

Preparation of βCD−Guest Gels(*x*). To construct supramolecular hydrogels with a high elasticity, self-healing properties and shape memory, selected adamantane (Ad) derivatives (TPAd10k and OPAd15k) as the guest group because the Ad derivative is one of the best guest molecules for βCD. Figure 5-1 depicts the chemical structure of the supramolecular hydrogels (βCD−Guest gels(*x*)). *x* represent the feed ratio of β-cyclodextrin acrylamide (AAm−βCD) and Ad units, respectively. Prior to the preparation of βCD−Guest gel, each Ad derivetives was dissolved in water by AAm−βCD to give an inclusion complex. After dissolving, the author polymerized the solution of a mixture of AAm-βCD and each terminal-guest-modified star-PEG (guest-PEG) with AAm by APS and TEMED. The solution produced supramolecular hydrogels, which was called βCD-TPAd10k gel, βCD-OP15k gel and TPAAm10k gel (Figure 5-2). When a mixture in water or DMSO is heterogeneously polymerized with the same initiator, heterogeneous radical copolymerization does not prodce a supramolecular hydrogels. Additionally, the homogeneous radical copolymerization in DMSO does not produce a gel. The βCD−Guest gels lack chemical cross-linking molecules, indicating that host−guest interactions stabilize the βCD−Guest gels as noncovalent cross-linkers.

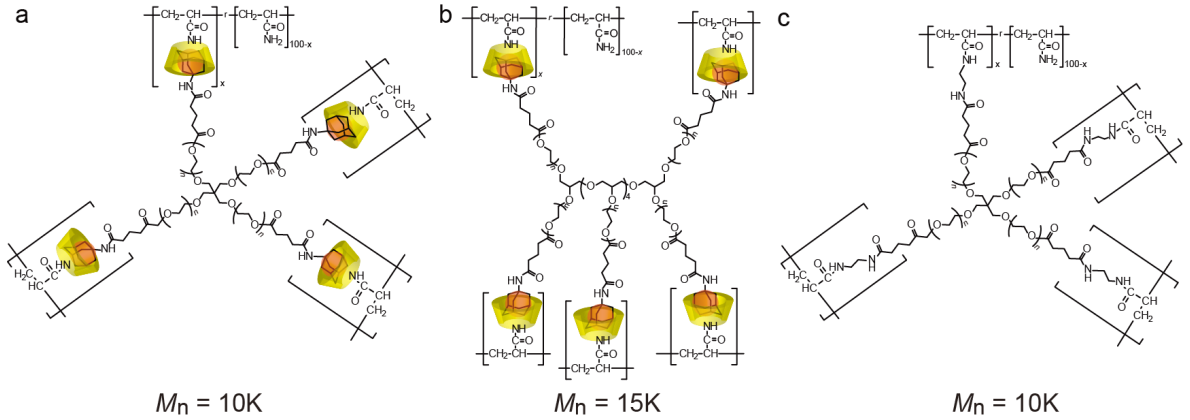


Figure 5-1. Chemical structures of βCD-TPAd(10, 15 and 40)k gel, βCD-OPAd15k gel, TPAAm gel(*y*) and AAm gel(5).

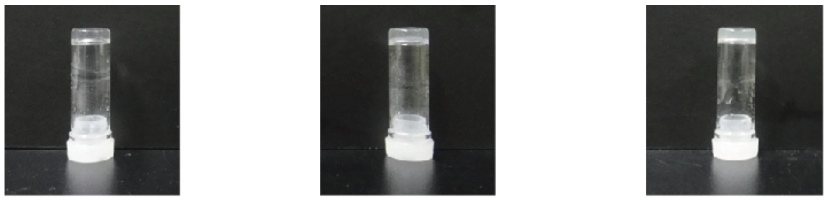


Figure 5-2. Iamges of the βCD-TPAd10k gel, theβCD-OPAd15k gel and TPAAm10k gel after polymerization of inclusion complexes between βCD and guest-PEG (TPAd10k and OPAd15k).

The mix of host polymer and guest star-shaped polymer. To investigate effect of preorganizing on formation of supramolecular hydrogels, 2 wt% solution of host polymer and guest-PEG were mixed in 1:1 (volume ratio). The βCD polymer as the host polymer was prepared by radical copolymerization of AAm-βCD and AAm with APS and TEMED in DMSO. Mixtures, βCD/TPAd10k and βCD/OPAd15k, were not produced supramoleculer hydrogels. When the author polymerized the βCD monomer, guest-PEG and AAm in water, the reacted solution yielded supramolecular hydrogels. For evaluating formation of inclustion complexes between polymers, the viscoelasticity analyzed mixtures of host polymer and guest-PEG. Figure 5-3 showed images of the sample after and before mixing host and guest solution with the viscosity by dynamic viscoelastic measurement. The viscosity of mixed solutions were obtained almost same value of the host polymer and guest-PEG. If host and guest molecules will form inclusion complexes into the solution, the viscosity of mixtures increase because cross-linking mol ratio have relations with the mechanical properties. However, the viscosity was not changed after mixing, indicating that the βCD and the Ad was hard to form inclusion complexes for building supramolecular hydrogels. These results indicated that the preorganized inclusion complex plays an important role in the formation of a supramolecular hydrogel.

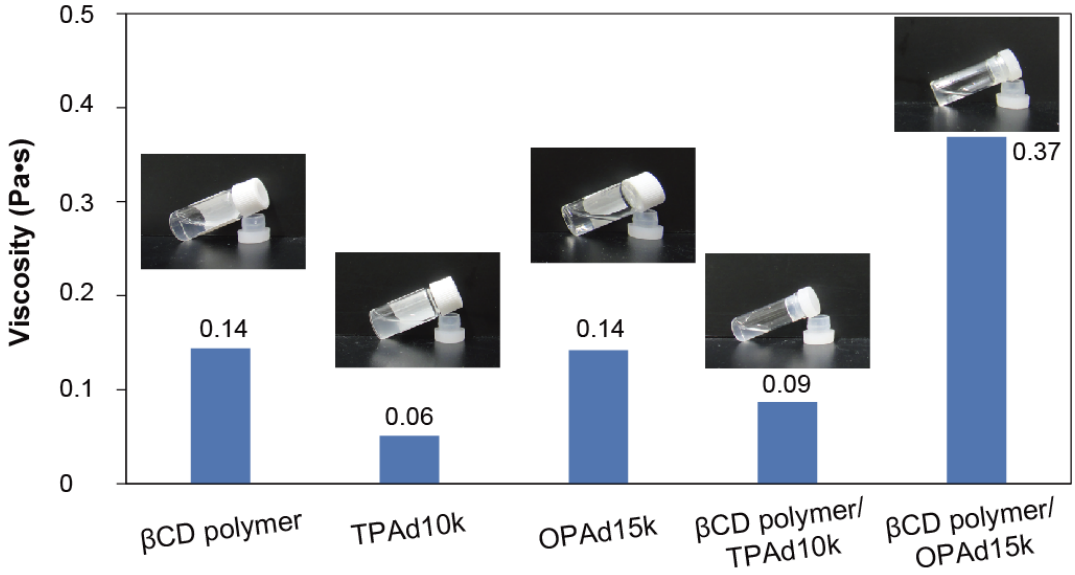


Figure 5-3. The viscosity of βCD polymer, TPAd10k, OPAd15k, the mixture of βCD polymer and TPAd10k and the mixture of βCD polymer and OPAd15k at 2 wt% (10 rad·s^{-1}, 0.1 %, ϕ = 25 mm).

Mechanical properties of βCD-Guest gels. Figure 5-5a and Figure 5-5b show the storage elastic modulus (G') and loss elastic modulus (G'') for βCD-Ad gels. G' values were larger than G'' values in the frequency region of 0.1-100 s^{-1}. Moreover, G' of the TPAAm10k gel were larger than G'' in the same region. Figure 5-5c and Figure 5-5d show the G' and G'' of βCD-Guest gels and TPAAm gels depend on strain in the region of 0.01% - 100% at 10 rad·s^{-1}. The G' and G'' of the βCD-TPAd10k gel and the βCD-OPAd15k gel was constant value in this region. However, the G' of TPAAm gels decreased with increasing the strain and the G'' increased at the same time. These phenomena of TPAAm gels were broken by increasing strain, suggested that the βCD-Guest gel has stretching properties, which was higher than TPAAm gels. G' and G'' of βCD-Guest gel increased the values with increasing molecular weight of guest-PEG, suggesting that the close distance between inclusion complexes as a cross-linking units was effectively forms cross-linked inside βCD-Guest gel (Figure 5-6). Additionally, G' and G'' values of the βCD-TPAd10k were

smaller than that of the βCD-OPAd15k. G' and G'' values of TPAAm gels were larger than βCD-TPAd10k gels and βCD-OPAd15k gel. In general, the force of a chemical binding (C-C) was larger than the force of supramolecular cross-linking (i.e., host-guest interaction). Thus, the material strength of TPAAm gels were strong in same cross-linked mol ratio of βCD-TPAd gels and the βCD-OPAd15k gel.

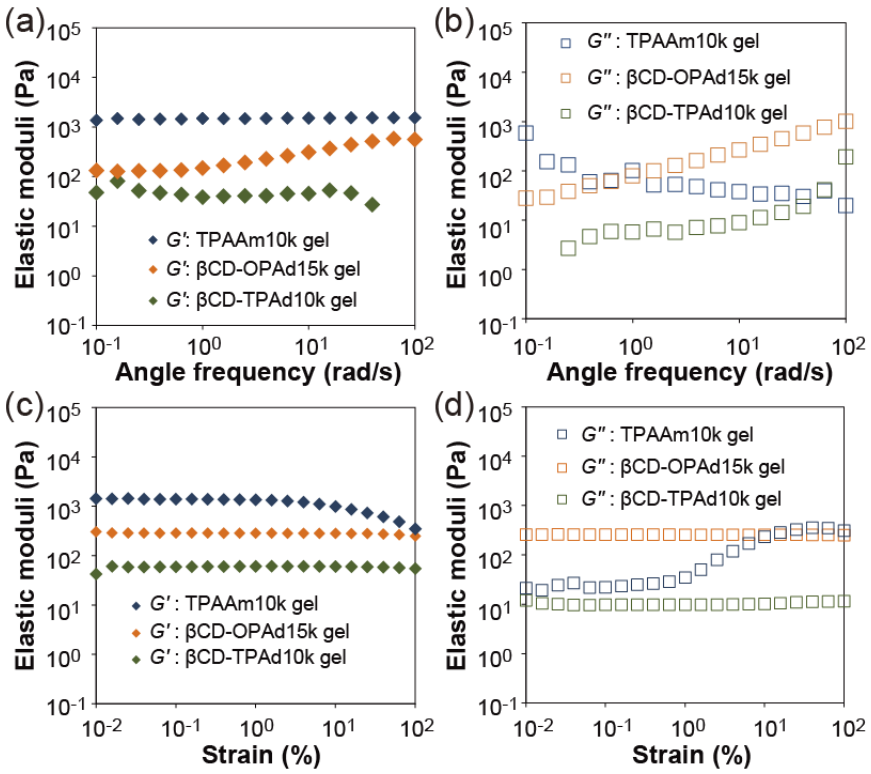


Figure 5-5. The G' and G'' of the βCD-TPAd10k gel (gleen), the βCD-OPAd15k gel (orange) and the AAm gel (blue) depend on (a) and (b) frequency or (c) and (b) strain.

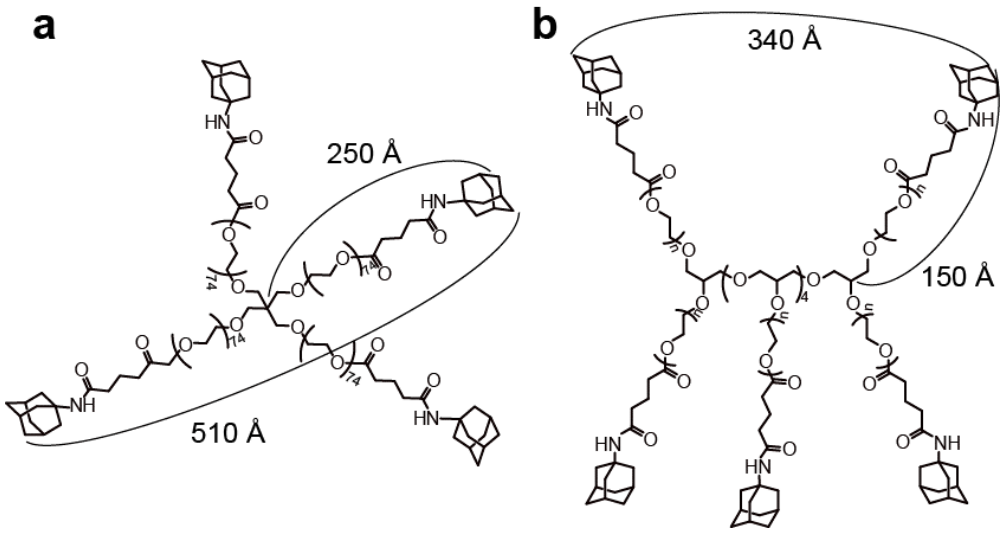


Figure 5-6. The longest molecular distance of TPAd10k and OPAd15k. The PEG unit was 3.3 Å calculated by molecular mechanics.

Self-healing behavior of βCD-Guest gel(*x*). βCD-Guest gels exhibit a self-healing property because the hydrogel has a reversible host-guest interaction between the side chains of the βCD polymers and the terminal of guest-PEG. Rectangular-shaped βCD-Guest gels were cut in half using a razor. Figure 5-8 shows self-healing behavior of the βCD-TPAd10k gel and the βCD-OPAd15k gel, respectively. The βCD-OPAd15k gel sample immediately mends after being broken; the gel can be lifted against its own weight. The βCD-TPAd10k gel sample mend slowly, but the two cut pieces reattach to form a single gel after standing for a few hours. However, the TPAAm gel did not show the self-healing behavior, when the two cut gel pieces rejoined to form a single gel after 24 hours. These results indicated that βCD-Guest gel exhibited self-healing properties via host-guest interaction and suggested that the self-healing properties of the βCD-TPAd gel were higher than the βCD-OPAd gel.

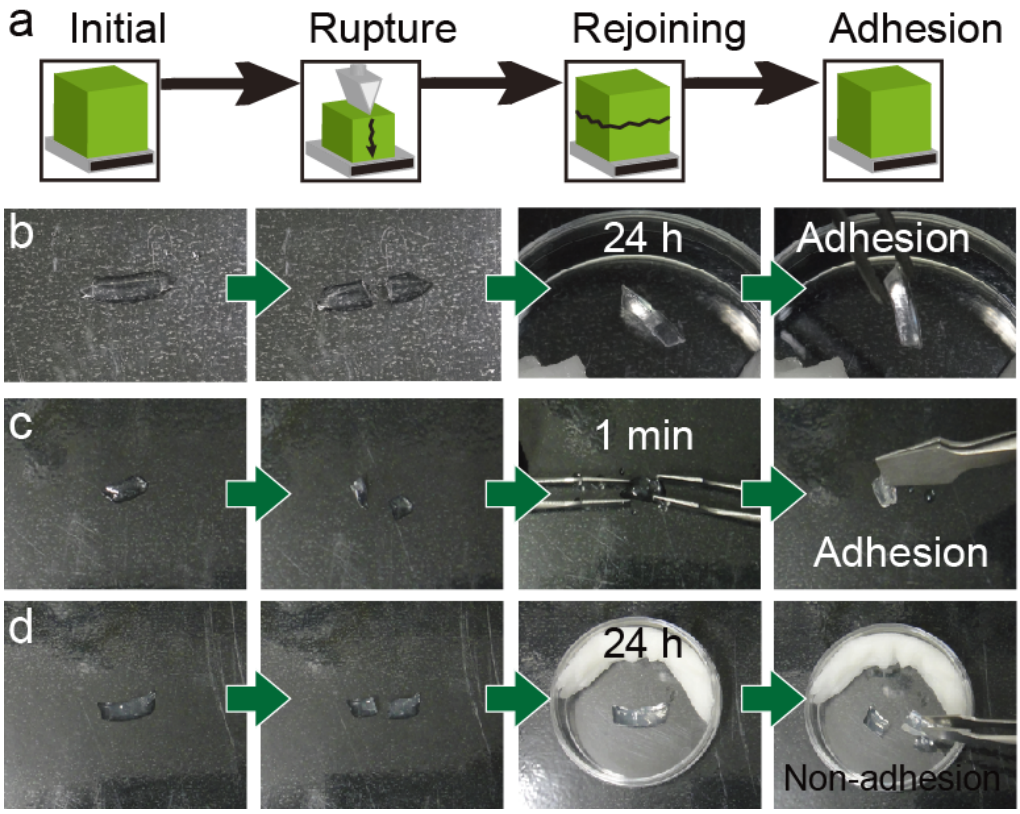


Figure 5-8. Shape recovery behavior of βCD−Ad gel(0.3, 0.4) using tweezers.

5-4. Conclusion

In *Chapter 5*, the author investigated mechanical and self-healing properties of materials cross-linked by inclusion complexes between βCD and terminal-guest-modified tetra-PEG (guest-PEG) which have some molecular weight (10k, 15k and 40k). Although the mixture of βCD polymer and guest-PEG does not formed the gel, the gel cross-linked by βCD and guest-PEG (βCD-Guest gel) was formed by polymerization of inclusion complexes. The βCD-Guest gel showed highly stretching and self-healing behavior. In particular, the βCD-TPAd10k gel has higher self-healing properties than the βCD-OPAd15k gel. The βCD-TPAd10k gel was farther than the βCD-OPAd15k gel, suggested that the distance between cross-linking units of the βCD-Guest gel was related with self-healing properties.

References

1. Dry, C.; Mcmillan, W. *Smart Mater. Struct.* **1997**, *6*, 35.
2. White, S. R.; Sottos, N. R.; Geubelle, P. H.; Moore, J. S.; Kessler, M. R.; Sriram, S. R.; Brown, E. N.; Viswanathan, S. *Nature* **2001**, *409*, 794.
3. Yang, Y.; Urban, M. W. *Chem. Soc. Rev.* **2013**, *42*, 7446.
4. Bergman, S. D.; Wudl, F. *J. Mater. Chem.* **2008**, *18*, 41.
5. Imato, K.; Nishihara, M.; Kanehara, T.; Amamoto, Y.; Takahara, A.; Otsuka, H. *Angew. Chem. Int. Ed.* **2012**, *51*, 1138.
6. Cordier, P.; Tournilhac, F.; Soulie-Ziakovic, C.; Leibler, L. *Nature* **2008**, *451*, 7925.
7. Wang, Q.; Mynar, J. L.; Yoshida, M.; Lee, E.; Lee, M.; Okuro, K.; Kinbara, K.; Aida, T. *Nature* **2009**, *463*, 339.
8. Burnworkth, M.; Tang, L.; Kumpfer, J. R.; Duncan, A. J.; Beyer, F. L.; Fiore, G. L.; Rowan, S. J.; Weder, C. *Nature* **2011**, *472*, 334.
9. Burattini, S.; Greenland, B. W.; Chappell, D.; Colquhoun, H. M.; Hayes, W. *Chem. Soc. Rev.* **2010**, *39*, 1973.
10. Kumpfer, J. R.; Rowan, S. J. *J. Am. Chem. Soc.* **2011**, *133*, 12866.
11. Behl, M.; Razzaq, M. Y.; Lendlein, A. *Adv. Mater.* **2010**, *22*, 3388.
12. Lendlein, A.; Shastri, V. P. *Adv. Mater.* **2010**, *22*, 3344.
13. Ratna, D.; Kocsis, J. K. *J. Mater. Sci.* **2008**, *43*, 254.
14. Liu, C.; Qin, H.; Mather, P. T. *J. Mater. Chem.* **2007**, *17*, 1543.
15. Sakai, T.; Matsunaga, T.; Yamamoto, Y.; Ito, C.; Yoshida, R.; Suzuki, S.; Sasaki, N.; Shibayama, M.; Chung, UI. *Macromolecules* **2008**, *41*, 5379.
16. Matsunaga, T.; Sakai, T.; Akagi, Y.; Chung, UI. Shibayama, M. *Macromolecules* **2009**, *42*, 6245.

Summary

In this thesis, self-healing materials through host-guest interactions were prepared by polymerization of inclusion complexes using cyclodextrin and alkyl compounds in water. Furthermore, these materials exhibited high stress healing ratio and highly elastic properties.

In *Chapter 2*, the author successfully prepared self-healing CD-guest gels crosslinked between poly(acrylamide) chains with inclusion complexes. The obtained CD-guest gels exhibit a self-standing property without chemical crosslinking reagents, indicating the newly formed host-guest interactions between the CD and the guest units stabilize the conformation of the CD-guest gels. The CD-guest gels display selective adhesion between cut surfaces and the initial stress strength is recovered. Hence, the formation of complementary complexes and the polymerization of inclusion complexes in aqueous solutions play important roles in creating self-healing CD-guest gels.

In *Chapter 3*, the mechanical properties of the host-guest gel without a chemical cross-linker were investigated by tensile experiments. The βCD−Ad gel(0.3, 0.4) shows high stretching (breaking strain: 960%) and high recovery properties (residual strain: 0.0%) within 220% of the yield point even with low contents of host and guest units. On the other hand, poly(acrylamide) gel, which lacks a supramolecular cross-linker, does not exhibit stretching and recovery properties. The addition of competitive molecules suppresses the stretching and recovery properties. The supramolecular cross-linker functions as flexible and sacrifice bonds to produce the stretching and recovery properties of βCD−Ad gel(*m*, *n*). Controlling the properties of the host−guest gels creates an innovative use of supramolecular hydrogels.

In *Chapter 4*, the adhesive strength between plastics containing β-cyclodextrin or adamantane was investigated in semi-wet condition to create self-adhesive materials. The

adhesive strength between plastics containing β-cyclodextrin (βCD P(*x*)) or adamantane (Ad P(*y*)) is greatly influenced by adding competitive molecules and the molar ratio of the βCD and Ad units, suggesting that the host–guest interactions between βCD and Ad units fulfill an important role in the adhesion between βCD P(*x*) and Ad P(*y*). In addition, the author created a self-healable material constructed by inclusion complexes of βCD and Ad (βCD-Ad P(0.3, 0.4)), which show a relatively high stress healing ratio (88%) and high adhesive strength (2.8 MPa). These results suggest that β-cyclodextrin and adamantane function as glue on the molecular scale to achieve macroscopic adhesion.

In *Chapter 5*, the author investigated mechanical and self-healing properties of materials cross-linked by inclusion complexes between βCD and terminal-guest-modified tetra-PEG (guest-PEG) which have some molecular weight (10k, 15k and 40k). Although the mixture of βCD polymer and guest-PEG does not formed the gel, the gel cross-linked by βCD and guest-PEG (βCD-Guest gel) was formed by polymerization of inclusion complexes. The βCD-Guest gel showed highly stretching and self-healing behavior. In particular, the βCD-TPAd10k gel has higher self-healing properties than the βCD-OPAd15k gel. The βCD-TPAd10k gel was farther than the βCD-OPAd15k gel, suggesting that the distance between cross-linking units of the βCD-Guest gel was related with self-healing properties.

List of Publications

1. Kakuta, T.: Takashima, Y.; Nakahata, M.; Otsubo, M.; Yamaguchi, H.; Harada, A. "Preorganized Hydrogel: Self-Healing Properties of Supramolecular Hydrogels Formed by Polymerization of Host–Guest-Monomers that Contain Cyclodextrins and Hydrophobic Guest Groups" *Adv. Mater.* **2013**, *25*, 2849-2853. (Inside Front Cover)

2. Kakuta, T.: Takashima, Y.; Harada, A. "Highly Elastic Supramolecular Hydrogels Using Host–Guest Inclusion Complexes with Cyclodextrins" *Macromolecules* **2013**, *46*, 4575–4579.

3. Kakuta, T.: Takaaki, S.; Takashima, Y.; Harada, A. "Adhesion between Plastics Containing Cyclodextrins and Adamantane based on Host–Guest Interaction", to be submitted.

4. Kakuta, T.: Takaaki, S.; Takashima, Y.; Harada, A. "High Functional Supramolecular Materials using Star-Shaped Polymer Terminal Modified Guest Molecules and Cyclodextrins", to be submitted.

Patents

1. "自己修復性及び形状記憶性を有するゲル、及びその製造方法 (Self-Healable and Shape-Memory Gel and Production Method)" 特願 2012-103460 号, Harada, A.; Takashima, Y.; Kakuta, T., April 2012.

Other Papers

1. Takashima, Y.; Hatanaka, S.; Otsubo, M.; Nakahata, M.; Kakuta, T.; Hashidzume, A.; Yamaguchi, H.; Harada, A. “Expansion–contraction of photoresponsive artificial muscle regulated by host–guest interactions” *Nat. Commun.* **2012**, *3*, 1270.

2. Takashima, Y.; Kakuta, T.: Nakahata, M.; Harada, A. “Construction of Stimuli-Responsive Self-Healing Supramolecular Material Using Host-Guest Interaction” *Journal of the Society of Rubber Science and Technology* **2012**, *85*, 260.

3. Takashima, Y.; Kakuta, T.: Nakahata, M.; Harada, A. “Construction of Stimuli-Responsive Self-Healing Supramolecular Material Using Host-Guest Interaction” *Chemical Industry* **2012**, *63*, 415–420.

4. Takashima, Y.; Kakuta, T.: Nakahata, M.; Harada, A. “ホスト-ゲスト相互作用を利用した自己修復性超分子材料の作製とその刺激応答性 (Formation of Self-Healable Supramolecular Materials Using Host-Guest Interaction and Stimuli-Responsive Properties)” *Engineering Materials* **2013**, *61*, 47–52.