

Synthesis of Degradable Model Networks via ATRP and Click Chemistry

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Synthetic polymer networks have been the subject of extensive theoretical, physical, and chemical study over the past century^{1a,b} and are continuing to be employed in new applications.^{1c,d} The structurally simplest polymer networks are termed “model networks” (MNs) and are typically comprised of linear telechelic polymers, or macromonomers (MAC), covalently cross-linked through their end groups with multifunctional small molecules (Figure 1).² MNs are unique because the cross-link functionality is constant and predetermined, so that the molecular weight between cross-links is defined by that of the MAC, and the material is homogeneous with respect to cross-link density.² Well-defined pore sizes are therefore obtained, providing potential advantages for certain applications.³ Although MNs have well-defined structure, they are not considered “ideal” in a theoretical sense because they unavoidably contain some number of unreacted functionalities, chain entanglements, and inelastic loops.² Furthermore, the inherent polydispersity (PDI) of the MAC precursor leads to a corresponding dispersity of pore sizes. These variations from ideality can adversely affect the mechanical and chemical properties of the resulting material, and hence, much focus is placed on preparing more ideal MNs.

Due to their insolubility in all solvents, MNs are notoriously difficult to characterize by common chemical techniques. As a consequence, certain network parameters, such as the number of unreacted functionalities, are typically estimated from combining macroscopic measurements with theory. Recently, Patrickios and co-workers utilized a hydrolytically labile cross-linker for the degradation of model star polymer networks and size-exclusion chromatography (SEC) of the degradation products to verify the parent network structure.^{1c} To apply this concept of degradation and analysis to networks of linear MACs, a synthetic route capable of yielding MACs of low PDI that possess orthogonal cross-linking and degradation functionalities is necessary.

The copper(I)-catalyzed azide–alkyne cycloaddition (CuAAC) reaction^{4a,b} has emerged as the best example of “click chemistry,”^{4c} characterized by extraordinary reliability and functional group tolerance. This ligation process has proven useful for the synthesis of novel polymers and materials in many laboratories,⁵ and its unique characteristics make it an ideal reaction for MN cross-linking. We therefore envisioned an azide telechelic MAC and a multifunctional small molecule alkyne, the former with a cleavable functionality at its center, as fulfilling the requirements for a degradable MN. Organic azides are most often made from alkyl halides, and several groups have reported the quantitative post-polymerization transformation (PPT) of polymeric halides to azides

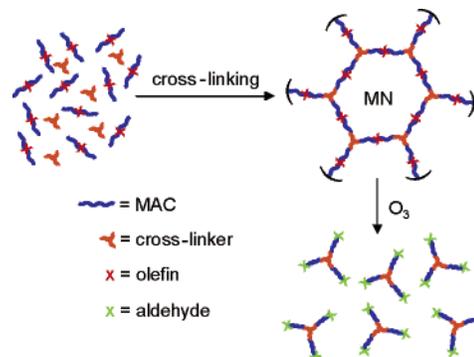
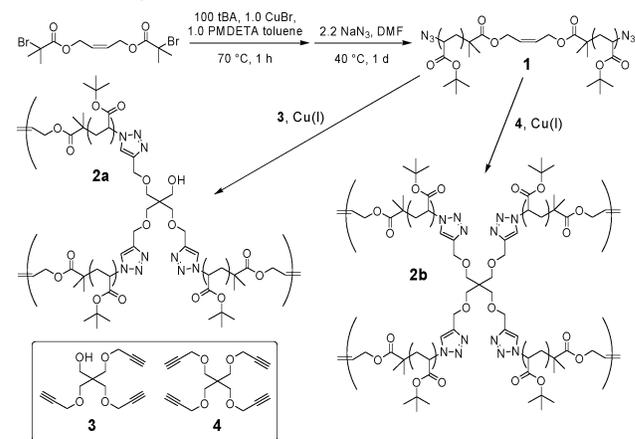


Figure 1. Schematic of MN synthesis and degradation.

Scheme 1. Synthesis of **1** and Structures of **2a**, **2b**, **3**, and **4**



for the CuAAC reaction by treatment with sodium azide in DMF.^{7a–c} Atom transfer radical polymerization (ATRP) of various styrenic, acrylic, and methacrylic monomers from halide initiators is well-known to provide polymers of low polydispersity possessing alkyl halide end groups.⁶ Therefore, by a sequence of ATRP from a degradable halide-containing initiator, PPT, and CuAAC, one can conveniently prepare MNs of different MAC structure (e.g., star polymers, block copolymers) and incorporate a wide variety of functional groups. We employed this scheme to prepare ozonizable *tert*-butyl acrylate (tBA) based MNs (**2a**, **2b**) comprised of an α,ω -azido-poly(tBA) MAC (**1**) cross-linked with tri- and tetraacetylene cross-linkers (**3** and **4**, respectively).

ATRP of tBA from the bifunctional initiator 1,2-bis(bromoisobutyryloxy)-2-butene (Scheme 1) gave α,ω -bromo-ptBA. The number average molecular weight (M_n) of this polymer was calculated by comparing the integration of the ¹H NMR resonances corresponding to the end group protons and the initiator protons to that of the

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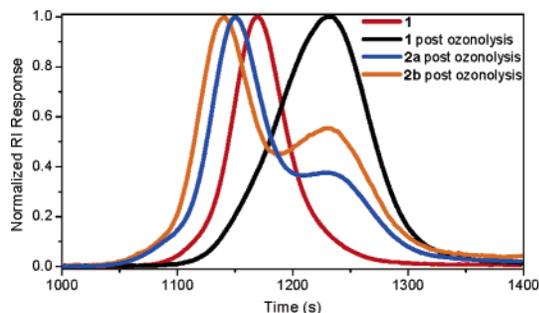


Figure 2. SEC traces of **1** before and after ozonolysis and the ozonolysis products of networks **2a** and **2b**.

tert-butyl protons present on each repeat unit. The value calculated in this manner ($M_{n(\text{NMR})} = 14.1$ kDa) was in excellent agreement with that obtained by SEC ($M_{n(\text{SEC})} = 14.4$ kDa), and the PDI was low (PDI = 1.12), as expected from ATRP. Treatment of this telechelic polymer with sodium azide in DMF yielded the desired MAC **1**. The success of the substitution reaction was indicated by the shift of the ^1H NMR resonance of the proton next to the end groups, the appearance of a strong absorbance in the IR spectrum characteristic of alkyl azide, and by elemental analysis showing the complete disappearance of bromine from the polymer.⁸ The CuAAC of **1** with **3** and **4** using CuBr, *N,N,N',N'',N'''*-pentamethyldiethylenetriamine (PMDETA) as ligand or base, sodium L-ascorbate (NaAsc) as reducing agent, and DMF solvent under argon atmosphere at 80 °C for 5 min yielded **2a** and **2b**, respectively, as insoluble materials. The IR spectra of the products closely resembled that of **1** without the azide peak,⁸ indicating that the cross-linking reaction consumed most of the azide groups. When no copper catalyst was employed, the azide peak remained unchanged, and when an approximately 2:1 ratio of azide to alkyne was used, the IR spectrum still displayed an azide resonance. The remaining azides and the olefin moiety can potentially be functionalized after cross-linking, providing another means of tailoring the properties of these materials. Furthermore, the *tert*-butyl esters of **2** can be hydrolyzed to form poly(acrylic acid) MNs.

A variety of CuAAC conditions were evaluated by measurement of the time required for insoluble material to form at 80 °C, and the CuBr/PMDETA/NaAsc/DMF system described above gave the fastest cross-linking (5 min) and thereby the best results.^{8,9} For example, CuBr/DMF (without PMDETA) and CuI/*N,N*-diisopropylethylamine/DMF both provided insoluble materials but required overnight reaction. The use of toluene instead of DMF gave parallel results over longer reaction times, with CuBr/PMDETA requiring hours instead of minutes to provide insoluble cross-linked material.

To determine the approximate amount of unreacted material left after CuAAC cross-linking and to confirm that the M_n between cross-links was well-defined, MNs **2a** and **2b** were ozonized to yield soluble products. Analysis by SEC (Figure 2) showed the ozonolysis product from **1** to have M_n approximately one-half that of **1** ($M_n = 7300$, PDI = 1.21) as would be expected considering that the olefin functionality is located at the center of **1**. On the basis of the hypothesized network structure for **2a** (Scheme 1), ozonolysis of the olefin moiety present at the midpoints of each junction can yield only four products,⁸ the major of which is a three-

armed star polymer with M_n equaling 1.5 times that of **1** (Figure 1). Similarly, the tetrafunctional MN **2b** is expected to give a major degradation product with M_n twice that of **1**. Figure 2 shows that both predictions are met, but both ozonized networks also show a peak corresponding to one-half the M_n of **1**. This peak must arise from cases in which only one, or neither, of the MAC azides reacted, or only one alkyne for a given cross-linker reacted. Sample **2b** showed more of this unreacted cross material, suggesting that the increased steric hindrance of a tetrafunctional network may limit the extent of cross-linking. It should also be noted that the polydispersity of **1** makes it impossible to precisely control the stoichiometry of azides to alkynes in the cross-linking reaction, and so a portion of the unreacted material in **2a** and **2b** may be due to an alkyne:azide ratio not exactly equal to one.

The general scheme of ATRP, PPT, and CuAAC overcomes many of the inherent difficulties of MN synthesis. We are now focused on further optimization of the cross-linking reaction, expanding the chemical diversity of these materials, and characterization of these materials for comparison to the predictions of polymer network theories. Also, we are employing the degradation/SEC method to screen the reactivity of various Cu(I) complexes in MN environments.

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Note Added after ASAP Publication. In the version published on the Internet April 27, 2006, there is an error in Figure 2 where **1a** and **1b** are referred to instead of **2a** and **2b**. The final version published April 28, 2006, and the print version are correct.

Supporting Information Available: Synthetic procedures, ATRP kinetics, and spectral data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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