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Abstract:

Covalent adaptable networks (CANs) are a newly emerging class of polymers that uniquely bridge the gap between traditional thermosets and thermoplastics. The distinguishing characteristic of these polymer networks is that they contain reversible crosslink bonds that allows these materials to be recycled. Two of the currently best-understood CAN systems include those based on Diels-Alder[1] and transesterification[2] reactions, both of which involve dissociative exchange mechanisms. Our group aimed to create a novel CAN system based on the thermal guanidine metathesis (TGM) reaction[3] by using a guanidine functional group as a crosslinker. In order to create a guanidine-crosslinked network, our research took a postpolymerization modification approach wherein we synthesized a precursor polymer containing pendant reactive carbodiimide functionalities which, upon reaction with a multifunctional amine, are reversibly converted into guanidine crosslinks. The carbodiimide-containing polymer is synthesized using free-radical copolymerization with styrene and a carbodiimide (CDI)-containing monomer with a styrenic substituent. The CDI-containing monomer is synthesized via creation and subsequent dehydrosulfurization of a thiourea-based pre-monomer. This research presents a comprehensive overview of the process of creating a reliable, scalable, 4-step synthetic plan to create a covalent adaptable network which uses a dissociable guanidine functional group as a covalent crosslink.

Introduction

Covalent adaptable networks (CANs) are a novel frontier in the field of polymer chemistry. Some unique properties found in CANs include self-healing abilities, resistance to thermal degradation, and reprocessability. The latter is becoming increasingly relevant and desirable in the context of novel polymer development, as the lack of recyclability or reprocessability of classic thermosets becomes a more and more pervasive environmental concern. Due to their unique structures which enable them to be reprocessed multiple times, covalent adaptable networks offer a possible aid to this issue and are thus of much interest to investigate further.

Adding to the library of known polymer systems capable of undergoing dissociative exchange, a novel reaction termed thermal guanidine metathesis (TGM) was discovered by a past member of the Larsen group and has been since studied to be introduced into a polymer network as the basis for a CAN. Small molecule studies have been conducted to better understand the molecular mechanism through which this functional group is formed via the reaction of a carbodiimide (CDI) functional group with an amine.[4] These studies found that this guanidine metathesis process operates through a dissociative mechanism in which upon heating a guanidine is split into two components, one half containing a carbodiimide and the other an amine. Within this temperature-dependent equilibrium, the two reagents are then able to rejoin into a guanidine. If conducted in the presence of another amine, this process generates a newly substituted guanidine with altered physical and chemical properties. If conducted within the context of a guanidine-crosslinked polymer, this chemical mechanism paired with large-scale polymeric motion at elevated temperatures can be harnessed to reprocess these materials or allow them to relax physical stress.

Using this knowledge, we were then tasked with copolymerizing CDI-containing monomers with styrene monomers into a poly(styrene-*co*-CDI) statistical linear copolymer. In order to create such a polymer, a CDI-containing monomer with a styrenic handle capable of undergoing free radical copolymerization had to be created first. No such monomer exists at this time in a commercially available capacity, and therefore this research was additionally tasked with the synthesis of an appropriately substituted carbodiimide. In order to control the *N*, *N'*-substitutions of these monomers, precursor molecules based on the thiourea functional group were developed which could then be converted into carbodiimides. Ultimately this resulted in a 4-step synthetic scheme beginning with a thiourea-based pre-monomer and ending with a guanidine-crosslinked CAN.

Materials and Experimental Methods

^{1}H NMR spectra were recorded on a Bruker Avance III 500 MHz FT-NMR spectrometer. Chemical shifts are reported in delta (δ) units, expressed in parts per million (ppm) downfield from tetramethylsilane (TMS) using the residual protio-solvent as an internal standard (CDCl$_3$, [1]H: 7.26 ppm). Peaks are reported using the following format: chemical shift [multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet), coupling constant(s) (J in Hz), integral]. FT-IR spectroscopy was performed with a Thermo iS10 FT-IR with single bounce diamond ATR. Dry dichloromethane (DCM) was obtained from an Inert PureSolv solvent purification system.
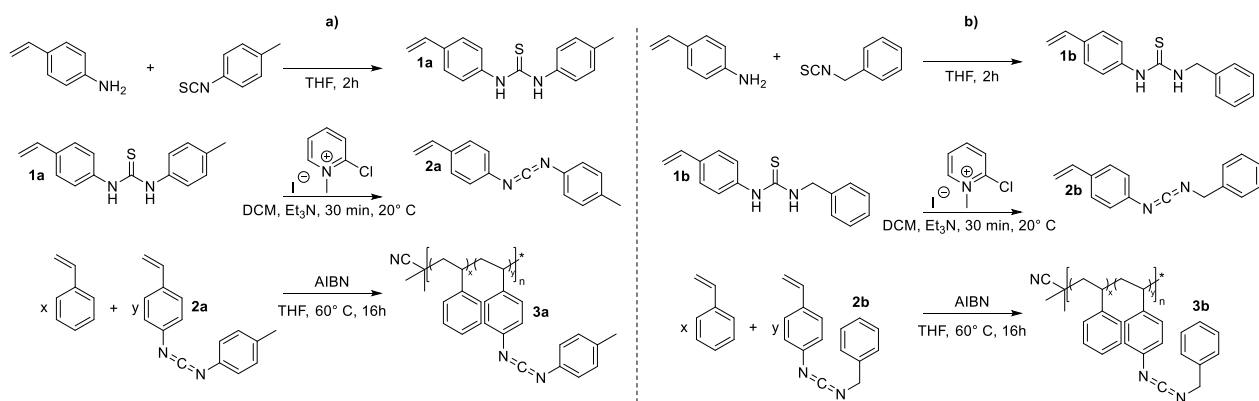

Figure 1. Overall scheme for synthesis of a) aryl-aryl disubstituted thiourea **1a**, carbodiimide **2a**, and poly(styrene-*co*-CDI) **3a** and b) alkyl-aryl disubstituted thiourea **1b**, carbodiimide **2b**, and poly(styrene-*co*-CDI) **3b**.
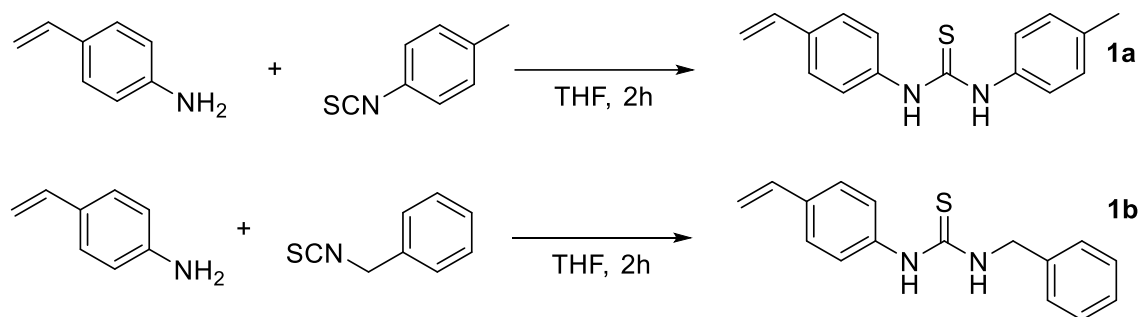
Figure 2. Synthesis of aryl-aryl disubstituted thiourea **1a** and alkyl-aryl disubstituted thiourea **1b**. The likely mechanism for this reaction follows a nucleophilic attack by the amine to the central carbon of the isothiocyanate followed by a proton transfer to result in the thiourea product.

1-(*p*-tolyl)-3-(4-vinylphenyl)thiourea. (**1a**) 4-vinylaniline (5.00 mL, 42.7 mmol) was added to a 50-mL round-bottom flask containing THF (30 mL). To this solution was added 1-isothiocyanato-4-methylbenzene (6.69 g, 44.81 mmol) and the reaction mixture was stirred for 2 hours. Reaction completion was confirmed via thin layer chromatography (2:1 hexanes:EtOAc). To the crude product was added hexanes (20 mL) to precipitate **1a** (8.69 g, 32.40 mmol, 75.9%) as a white crystalline solid. The crystals were recovered via gravity filtration and air dried overnight. Purity of the product was confirmed by FT-IR and ^{1}H NMR spectroscopy.
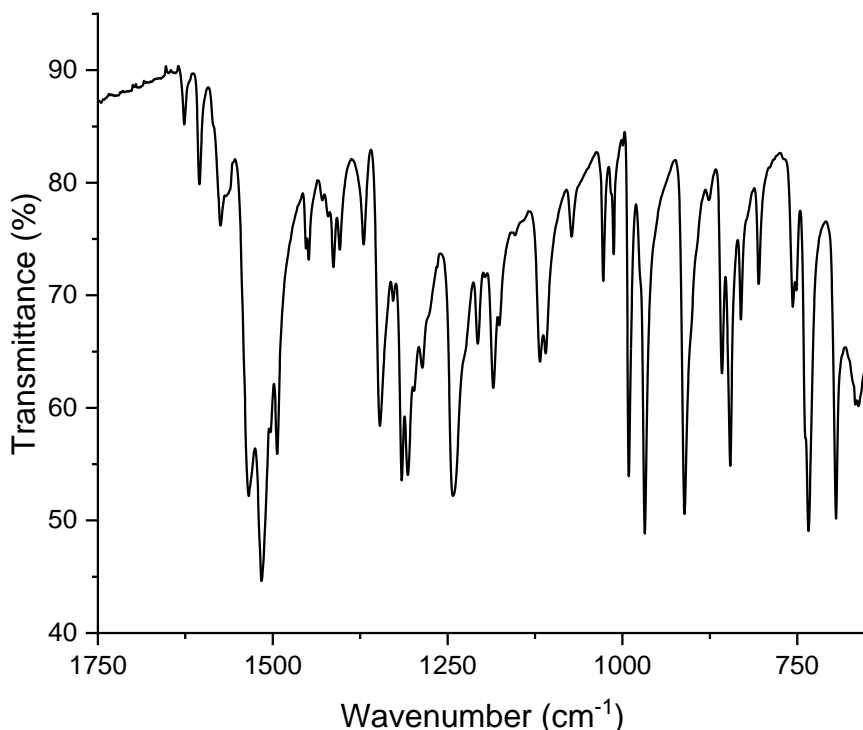

Figure 3. FT-IR spectrum of 1-(*p*-tolyl)-3-(4-vinylphenyl)thiourea (**1a**) from 1750-500 cm^{-1}. Thiourea C=S stretching mode peak is observed at ~1243 cm^{-1}.

^{1}H NMR (500 MHz, CDCl$_3$) δ 7.79 (bs, 1H), 7.74 (bs, 1H), 7.51 – 7.42 (m, 2H),7.38 (d, *J* = 8.5 Hz, 2H), 7.3-7.2 (m, 2H), 6.71 (dd, *J* = 17.6, 10.9 Hz, 1H), 5.75 (d, *J* = 17.6 Hz, 1H), 5.29 (d, *J* = 10.8 Hz, 1H), 2.39 (s, 3H).

1-benzyl -3-(4-vinylphenyl)thiourea. (**1b**) 4-vinylaniline (5.00 mL, 42.7 mmol) was added to a 100-mL round-bottom flask containing THF (30 mL). To this solution was added (isothiocyanatomethyl)benzene (3.56 mL, 26.9 mmol) and the reaction mixture was stirred for 2 hours. Reaction completion was suspected due to visible appearance of yellow oil **1b** (7.60g, 28.3 mmol, 66.4%) at bottom of reaction flask and confirmed via thin layer chromatography (TLC) (2:1 hexanes:EtOAc). Crude product was crystallized via rotary evaporation and washed threefold with hexanes (approx.. 15 mL) over gravity filter. Product was dried in air overnight and characterized by FT-IR and ^{1}H NMR spectroscopy.
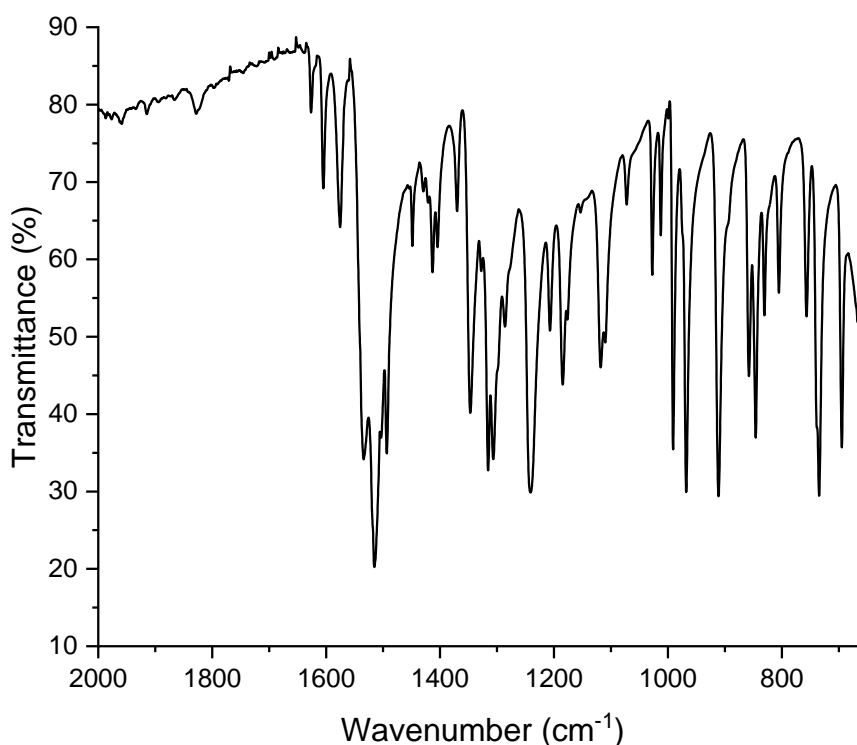

Figure 4. FT-IR spectrum of 1-benzyl-3-(4-vinylphenyl)thiourea (**1b**) from 2000-650 cm^{-1}. Thiourea C=S stretching peak is observed at ~1241 cm^{-1}.

^{1}H NMR (500 MHz, CDCl3) δ 7.66 (bs, 1H), 7.46 – 7.40 (m, 2H), 7.38 – 7.27 (m, 5H), 7.19 – 7.13 (m, 2H), 6.67 (dd, *J* = 17.6, 10.9 Hz, 1H), 6.23 (bs, 1H), 5.73 (d, *J* = 17.6 Hz, 1H), 5.29 (d, *J* = 10.9 Hz, 1H), 4.88 (d, *J* = 5.4 Hz, 2H).
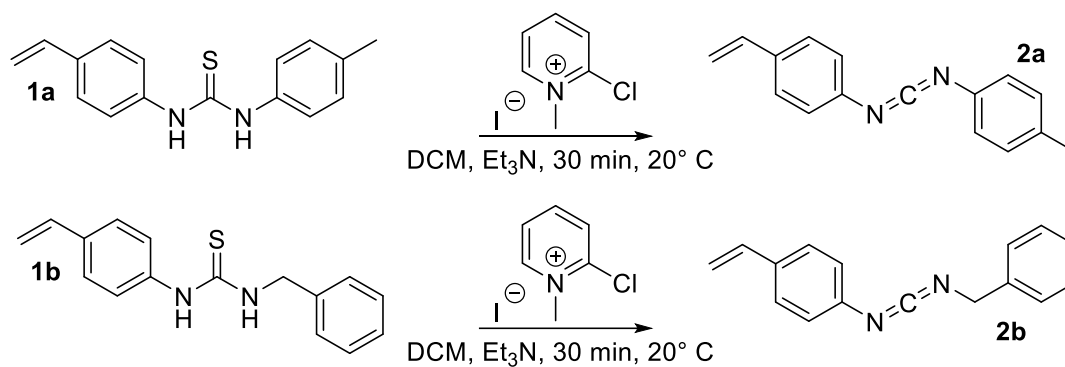
Figure 5. Synthesis of aryl-aryl disubstituted CDI **2a** and alkyl-aryl disubstituted CDI **2b** via thiourea dehydrosulfurization with Mukaiyama's reagent.

N-p-tolyl-N-(4-vinylphenyl)methanediimine. (**2a**) 1-(p-tolyl)-3-(4-vinylphenyl)thiourea (**1a**) (3.5 g, 13.04 mmol) was added to a dry flask under nitrogen containing dry DCM (30 mL) and 2-chloro-1-methylpyridinium iodide (4.00 g, 15.7 mmol). The flask was charged with dry triethylamine (5.45 mL, 39.1 mmol) and the mixture was stirred for 30 min. Reaction completion was confirmed via TLC . Excess solvent was removed via rotary evaporation and reaction mixture was redissolved in preparation for passage through a silica plug (2:1 hexanes:DCM). This was followed by removal of remaining solvent via rotary evaporation to give **2a** (2.71 g, 11.6 mmol, 88.6%) as a translucent, slightly yellow oil. FT-IR and ^{1}H NMR spectroscopy confirmed purity of product.
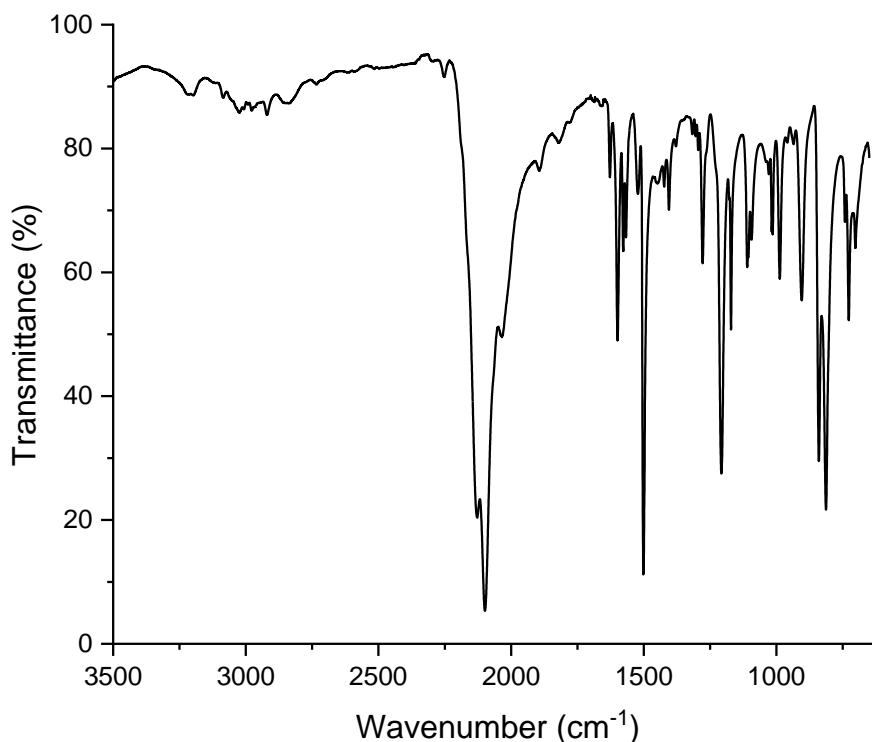
Figure 6. FT-IR spectrum of N-p-tolyl-N-(4-vinylphenyl)methanediimine (**2a**) from 3500-650 cm$^-$^{1}. Carbodiimide N=C=N stretching peak is observed at 2098 cm^{-1}.

^{1}H NMR (500 MHz, CDCl$_3$) δ 7.40 – 7.32 (m, 2H), 7.17 – 7.10 (m, 4H), 7.10 – 7.03 (m, 2H), 6.68 (dd, J = 17.6, 10.9 Hz, 1H), 5.71 (dd, J = 17.6, 0.8 Hz, 1H), 5.23 (dd, J = 10.8, 0.8 Hz, 1H), 2.33 (s, 3H).

N-benzyl-N-(4-vinylphenyl)methanediimine. (**2b**) The procedure for the synthesis and purification of **2a** was followed using **1b** (3.5 g, 13.04 mmol) in place of **1a**, dry DCM (30 mL), 2-chloro-1-methylpyridinium iodide (4.00 g, 15.7 mmol), and dry triethylamine (5.45 mL, 39.1 mmol) to yield **2b** (2.94 g, 12.6 mmol, 96.3%) as a colorless oil. FT-IR and ^{1}H NMR spectroscopy confirmed purity of product.
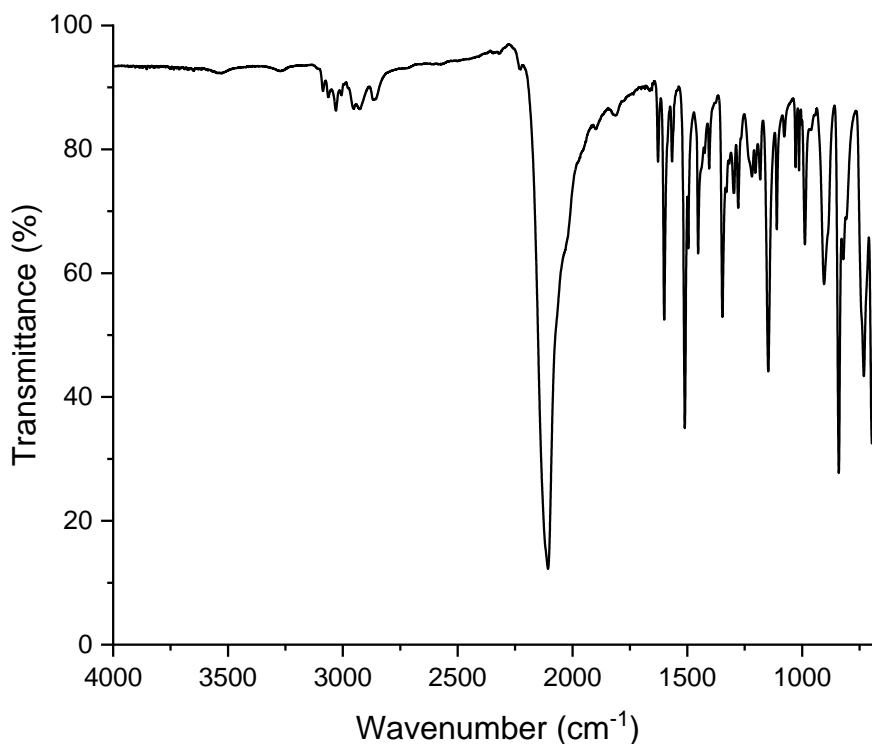

Figure 7. FT-IR spectrum of N-benzyl-N-(4-vinylphenyl)methanediimine (**2b**) from 4000-650 cm^{-1}. Carbodiimide N=C=N stretching mode peak is observed at 2109 cm^{-1}.

^{1}H NMR (500 MHz, CDCl$_3$) δ 7.38 (d, J = 4.4 Hz, 4H), 7.35 – 7.28 (m, 4H), 7.00 – 6.89 (m, 1H), 6.66 (dd, J = 17.6, 10.9 Hz, 1H), 5.67 (dd, J = 17.6, 0.9 Hz, 1H), 5.20 (dd, J = 10.8, 0.9 Hz, 1H), 4.58 (s, 2H).
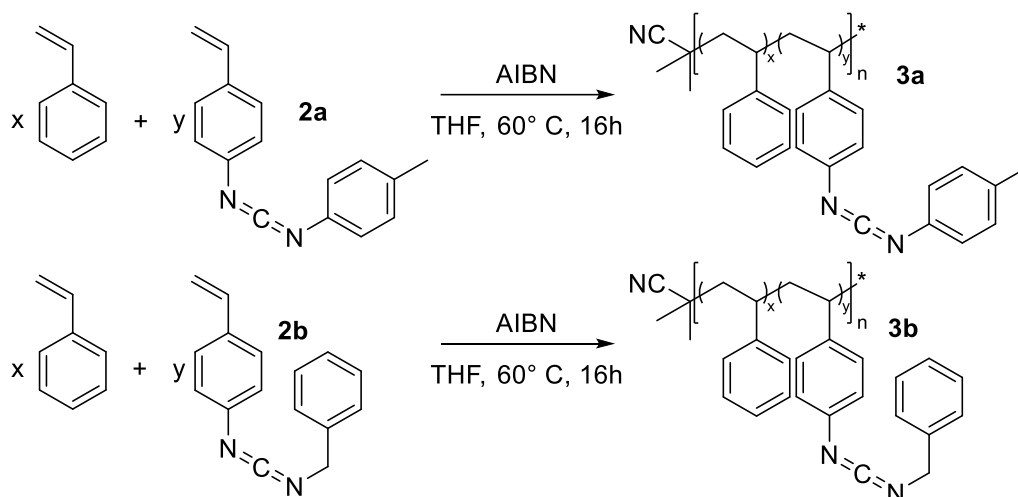
Figure 8. Overall reaction schemes for uncontrolled free-radical synthesis of poly(styrene-*co*-CDI) statistical copolymers **3a** and **3b** via copolymerization of carbodiimide monomers **2a** and **2b** with styrene initiated by AIBN.

Poly(styrene-co-carbodiimide). (**3a**) To a flame-dried 250-mL Schlenk flask containing THF (40 mL) was added **2a** (2.60 g, 11.1 mmol), styrene (23.12 mL, 221.9 mmol), and (E)-2,2'-(diazene-1,2-diyl)bis(2-methylpropanenitrile) (AIBN) (2.02 g, 12.3 mmol). The reaction flask was then sealed and the reaction mixture underwent three freeze-pump-thaw cycles. The headspace was backfilled with nitrogen after the final thaw and the reaction mixture was stirred at 60 °C for 16 hours, at which time the vessel was opened to air to terminate the reaction. The crude polymer mixture was precipitated dropwise into chilled methanol + 1% DI H_2O (400 mL). The precipitated polymer was recovered via vacuum filtration, redissolved in THF (40 mL), re-precipitated dropwise into an additional 400 mL methanol, and filtered once more to give **3a** (16.0 g, 53.8%) as a low-density white powder. The polymer was dried on a Schlenk line on high vacuum at 40 °C overnight to remove residual THF and methanol, then characterized by FT-IR, ^{1}H NMR, and GPC.

Characterization of the resultant polymer by ^{1}H NMR in solution with 1,3,5-trimethoxybenzene as an internal standard in known quantities allowed for the approximate calculation of both CDI functionality concentration within the polymer in units of mmol CDI per mg polymer as well as relative ratios of styrene to CDI to confirm statistical incorporation of both monomers (Figure 10). Average CDI concentration within copolymers of **2a** synthesized with 20:1 styrene:CDI loading is 5.47×10^{-4} mmol CDI per mg polymer. Average resultant styrene:CDI ratio was determined to be 12.5:1 for the same systems.
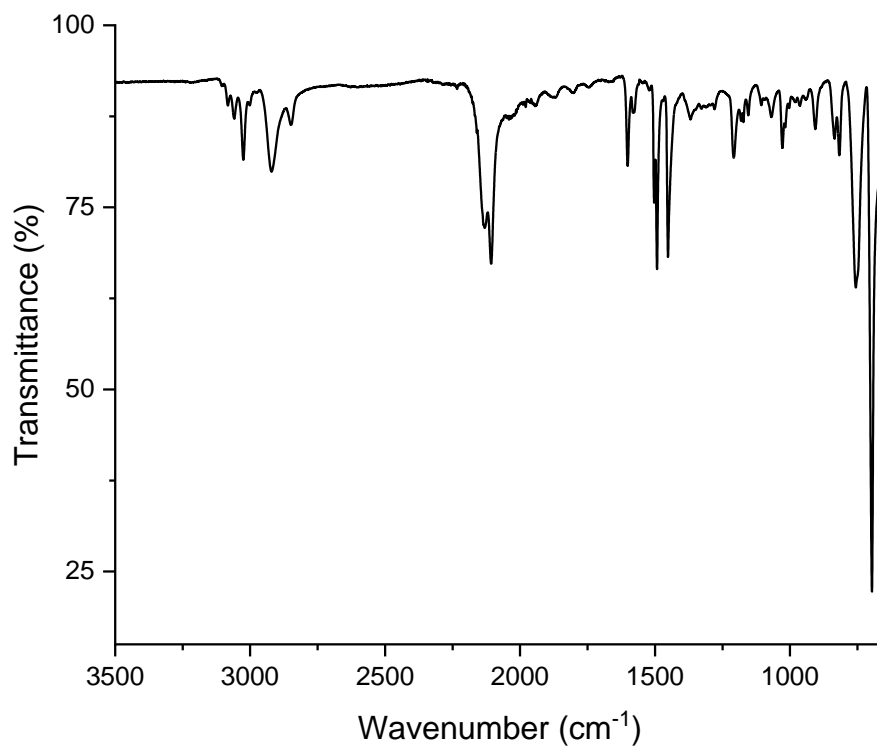
Figure 9. FT-IR spectrum of aryl-aryl disubstituted poly(styrene-*co*-CDI) **3a** from 3500-650 cm^{-1}. Carbodiimide N=C=N stretching mode peak is observed at 2119 cm^{-1}.
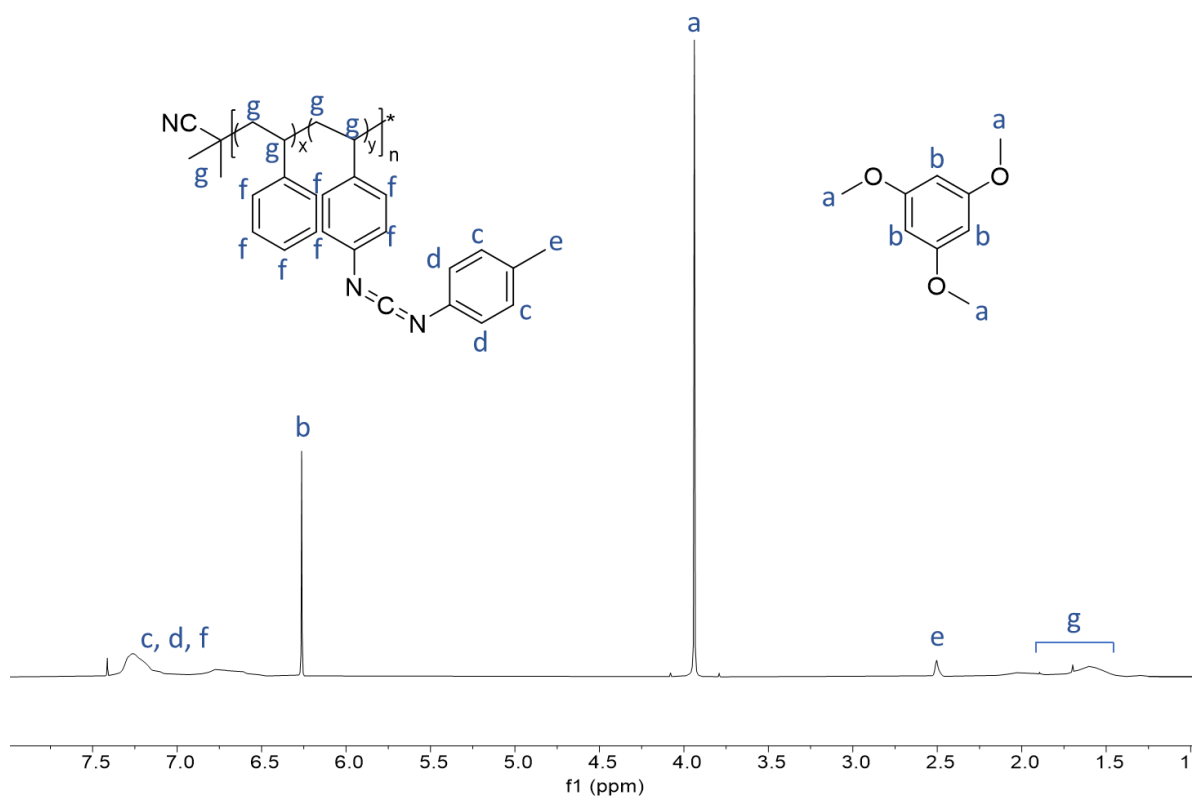
Figure 10. ^{1}H NMR spectrum for determination of CDI:styrene ratio of alkyl-aryl poly(styrene-*co*-CDI) **3b** using 1,3,5-trimethoxybenzene (peaks a and b) as an internal standard.
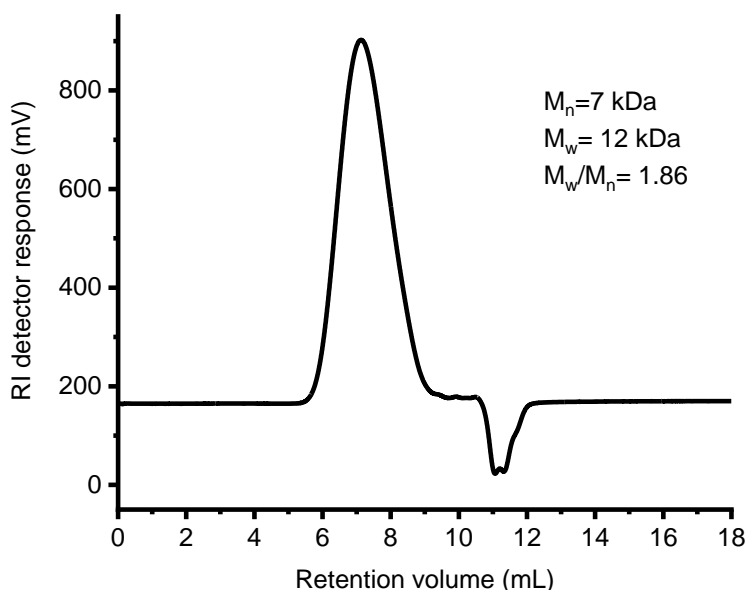

Figure 11. Representative gel permeation chromatogram of aryl-aryl poly(styrene-*co*-CDI) showing an average molecular weight of 7-12 kDa and a polydispersity of 1.86. Monomodal molar mass distribution indicates lack of unwanted crosslinking or branching side reactions.

Poly(styrene-co-carbodiimide). (**3b**) The procedure described for the synthesis and purification of **3a** was followed using **2b** (3.00 g, 12.8 mmol) in place of **2a**, styrene (29.58 mL, 256.1 mmol), and (E)-2,2'-(diazene-1,2-diyl)bis(2-methylpropanenitrile) (AIBN) (2.34 g, 14.2 mmol). This procedure gave **3b** (12.80 g, 43%) as a low-density white powder. The polymer was dried on a Schlenk line on high vacuum at 40 °C overnight to remove residual THF and methanol, then characterized by FT-IR and ^{1}H NMR.

Characterization of the resultant polymer by ^{1}H NMR in solution with 1,3,5-trimethoxybenzene as an internal standard in known quantities allowed for the approximate calculation of both CDI functionality concentration within the polymer in units of mmol CDI per mg polymer as well as relative ratios of styrene to CDI to confirm statistical incorporation of both monomers (Figure 13). Average CDI concentration within copolymers of **3b** synthesized with 20:1 styrene:CDI loading is 4.89×10^{-4} mmol CDI per mg polymer. Resultant styrene:CDI ratio has not been determined for enough of these systems to calculate an average.

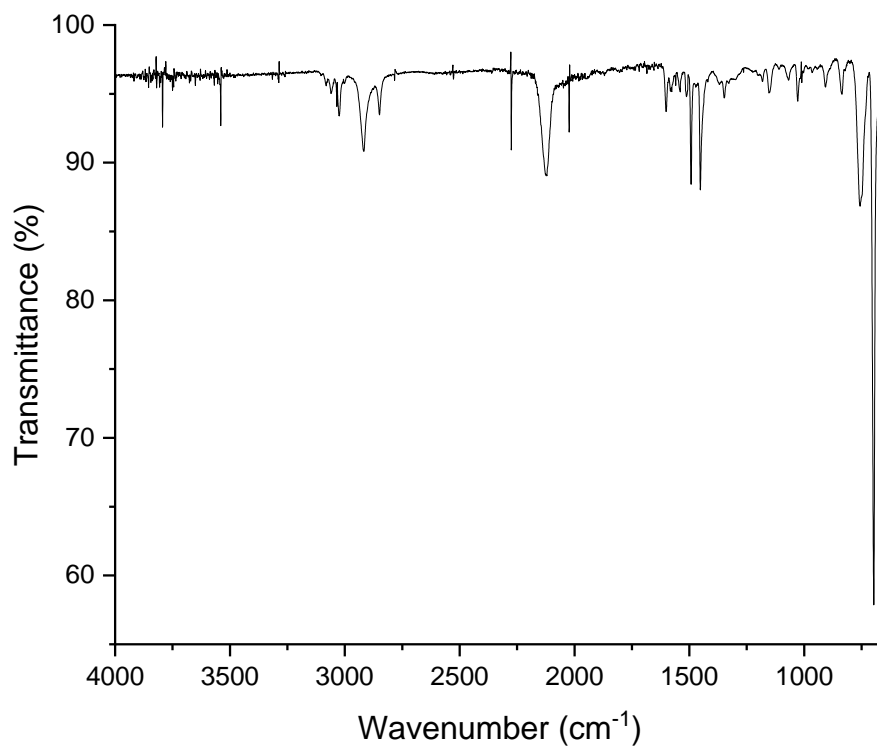**Figure 12.** FT-IR spectrum of alkyl-aryl poly(styrene-*co*-CDI) **3b** from 4000-650 cm^{-1}. Carbodiimide N=C=N stretching mode peak is observed at 2106 cm^{-1}.
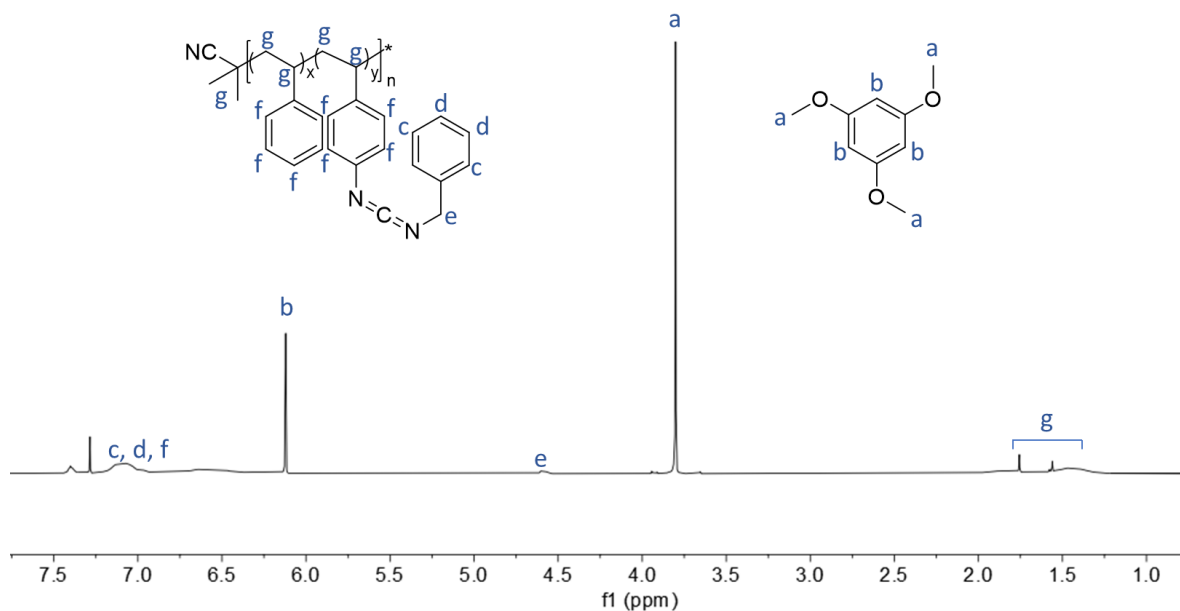
Figure 13. ^{1}H NMR spectrum for determination of CDI:styrene ratio of alkyl-aryl poly(styrene-*co*-CDI) **3b** using 1,3,5-trimethoxybenzene (peaks a and b) as an internal standard.

Guanidine-crosslinked covalent adaptable network. The linear poly(styrene-*co*-CDI) polymers were dissolved in THF and to the solutions were added solutions of piperazine and 5% (by total mass) dioctyl phthalate plasticizer in THF. The system immediately formed a clear, colorless gel which air-dried overnight to form a colorless disc that could be dried and processed. The resultant CAN was dried on a high vacuum line at 100 ºC overnight and subsequently further dried via placement in vacuum oven at 160 ºC for 2 hours. Following complete drying of the system, these materials can be processed into characterizable samples using a melt press. By pressing at high temperature and pressure, the CAN powder can be formed into homogeneous and translucent bars or discs that can be used for dynamic mechanical analysis (DMA) and rheological investigations. Via DMA and rheology we were able to empirically confirm that the CAN systems created using these polymers are capable of relaxing applied stress via a chemical mechanism. More information about studies into the rheological and mechanical properties of this polymer system are outside of the scope of this paper and therefore the synthesis and characterization of these systems will not be discussed in further detail in this report.

Results & Discussion

This report details the successful development of a 4-step synthetic scheme capable of the reliable and scalable production of guanidine-crosslinked polystyrene-based covalent adaptable networks. This process was conducted with two different monomer structures, though due to practical constraints we were only able to ultimately thoroughly investigate the styrenic aryl-aryl disubstituted carbodiimide-based CAN systems. Additionally, studies into alteration of the polarity of the polymer network by the copolymerization of monomers of styrenic CDI using methyl acrylate in place of styrene were largely unsuccessful. The successful development of a reliable synthetic approach for the production of large-scale batches of poly(styrene-*co*-CDI) as described in this report has opened the door for endless new avenues for the investigation of guanidine-based CAN systems.

Future research to be conducted includes investigation of the variation of guanidine structure via reaction of pendant CDI subunits with multifunctional amines of various N-substitution, including ethylenediamine and *trans*-2,5-dimethylpiperazine. Of further interest to our research group is further investigation into the copolymerization of our styrenic CDI monomers with more polar acrylate monomers. Additionally, further studies to be conducted on our polystyrene-based systems include investigation of the effects of increasing and decreasing the loading of CDI monomers relative to styrene, which would ultimately result in an increase or decrease in crosslink density of the CAN systems, the result of which would be a set of rheological properties that are not yet well studied or understood within any previously studied CAN systems.

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