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Article

Effects of Thiol Substitution on the Kinetics and Efficiency of Thiol-Michael Reactions and Polymerizations

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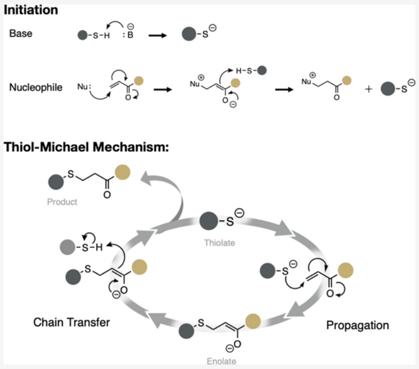
ABSTRACT: The kinetic effects of the substitution and functionality of the thiol in thiol-Michael reactions were investigated using model monofunctional thiols and multifunctional thiols used in various cross-linking polymerizations. The differences in kinetic rates and final conversions were observed *via* Fourier transform infrared spectroscopy. The shelf life of these polymers and their mechanical properties were analyzed using a rheometer to measure viscosity changes over time. It was concluded that for monofunctional systems, the reaction rate is dependent on both electronic and steric interactions. For systems with a propagation rate-limiting step (propionate), the secondary thiol was faster than the primary thiol due to increased reactivity of the thiolate anion, by as much as much as a 60% increase in the rate. However, more sterically hindered internal alkenes resulted in primary and secondary rates about equal to each other. For systems with a chain transfer-limiting step (alkyl thiol), the rate was dependent on the pK_a of the thiol and ease of deprotonation; in these cases, the primary thiol was the fastest. Though primary and secondary thiols had relatively mild differences in rates, reactions of tertiary thiols were slower than either of the others. For polymerizing systems using multifunctional thiols, the results varied depending on the substitution and functionality. When reacting with a difunctional alkene, the secondary thiol was 74−95% faster than the primary thiol, depending on the type of thiol assessed, and as the functionality of the alkene increased, the rates became more comparable. In the tetrafunctional alkene systems, the primary thiol was 57% faster than the secondary thiol. The shelf life of the systems produced varied results. Typically, in systems with the difunctional thiol, the primary thiol formulation was significantly less stable and gelled more rapidly than the resin with the corresponding secondary thiol. However, in the tetrafunctional thiol systems, the resin containing the secondary thiol gelled more rapidly than that containing the primary thiol. All systems typically gelled within 30 days regardless of substitution, although no additional formulation adjustments were made to stabilize any of these systems beyond changing the thiol structure.



INTRODUCTION

The thiol-Michael click reaction was first noted in the 1960s,[1] and it exhibits many exceptional characteristics that make this reaction desirable for a variety of applications including dendrimer synthesis,[2,3] surface functionalization,[4,5] hyperbranched polymers,[6] and polymer synthesis.[7,8] These characteristics—rapid kinetics with few side products, high functional group conversion, lack of oxygen inhibition, and mild reaction conditions that can proceed solventless or using environmentally benign solvents[9,10]—arise from the mechanism of the reaction and have led to this reaction being considered, under appropriate conditions, a click reaction.[10] This addition reaction takes place between thiols and electron-deficient alkenes, rapidly reaching high quantitative conversions and being readily catalyzed by either basic or nucleophilic initiators.[11] When using a base catalyst, the base abstracts a hydrogen from a thiol to generate the thiolate anion. During nucleophilic initiation, the nucleophile first adds to the double bond of the Michael acceptor, generating an enolate that then abstracts a hydrogen from the thiol to generate the thiolate anion (Figure 1).

In both the basic and nucleophilic mechanisms, the thiolate then acts as the Michael donor, attacking the electron-deficient β-carbon of the alkene during the propagation step of this reaction (Figure 1). The generated enolate anion then abstracts a proton from the thiol in a chain transfer step, regenerating the thiolate anion to continue the cycle of this reaction. Past research has shown that the thiol-Michael reaction is affected by solvent polarity, thiol basicity, base strength, and electron deficiency of the vinyl group.[12] Additionally, the steric hindrance of the reactants affects the

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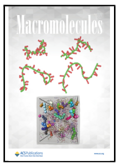

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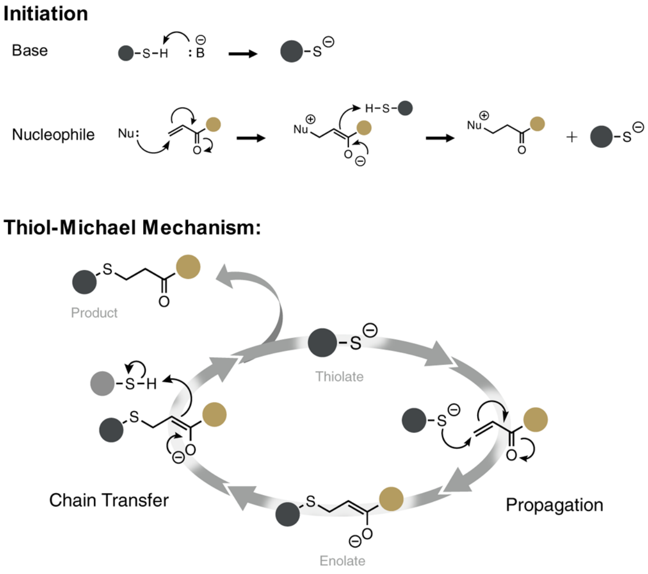

Figure 1. Initiation and the thiol-Michael mechanism. For base-catalyzed reactions, a base abstracts a hydrogen yielding a thiolate anion, which proceeds directly into the thiol-Michael reaction. For nucleophile-catalyzed reactions, a nucleophile attacks the unsaturated β-carbon of the Michael acceptor. The resulting enolate then abstracts a hydrogen from a thiol to generate the thiolate anion. The leftover product from the catalyst's nucleophilic attack is an inherent side product. The thiolate anion attacks the unsaturated β-carbon of the Michael acceptor generating a negatively charged enolate. The enolate then abstracts a hydrogen from a new thiol, reproducing the thiolate anion, as well as the thioether product.

thiol-Michael reaction—the larger the substituents at the α and β positions on the Michael acceptor, the slower the reaction.[13] Additionally, if the steric hindrance around the nucleophile increases, its reactivity decreases.[14]

However, it has been shown that in thiol−ene reactions, where a thiol adds radically to an alkene,[15] increasing the steric hindrance around the thiol molecule does not imbue dramatic decreases in the reaction rate, and in some conditions, any difference in the kinetic rate was negligible.[16] This behavior could be due to the large atomic radius of the sulfur atom and the increased nucleophilicity, any changes in sterics have relatively reduced effects when compared to the size of the larger sulfur atom. Additionally, the secondary thiol and alkene mixtures were found to have a longer shelf life and the secondary thiol monomers were reported not to have any odor.[17] Therefore, this work seeks to determine how more substituted thiols will affect the thiol-Michael reaction, as there are few, if any, literature sources that discuss how the substitution of the thiol affects the thiol-Michael reaction. Consequently, model reactions using monofunctional thiols were completed to observe the effect of increased substitution in the thiol-Michael systems without added complexities from polymerizations, such as gelation and diffusion limitations. Fourier transform infrared (FTIR) spectroscopy was used to observe the reaction kinetics and conversion changes in real time. Additionally, secondary analogues of the most common thiol monomers used in the thiol-Michael studies were selected for further polymerization kinetic analysis and shelf-life assessments of the resin stability. The findings of this study provide a foundational understanding of thiol reactivity in the thiol-Michael reactions.

■ EXPERIMENTAL SECTION

Materials. The thiols, *n*-butane thiol (NBT) and *tert*-butylthiol (TBT), and alkenes, ethyl vinylsulfone and hexylacrylate, were purchased from Sigma-Aldrich. *sec*-Butylthiol (SBT) was purchased from VWR International. The alkene, pentaerythritol tetraacrylate, was purchased from Tokyo Chemical Industry. 1,4-Butanediol diacrylate was purchased from Fisher Scientific. The photobase, 2-(2-nitrophenyl)propyloxycarbonyl-1,1,3,3-tetramethylguanidine (NPPOC-TMG), was synthesized in the laboratory, following the reaction proposed by Zhang *et al.*[18] Diethyl fumarate was obtained from Alfa Aesar, and 1,4-butanediol bis(mercaptopropionate) was purchased from Wako Chemicals. All deuterated solvents were purchased from Cambridge Isotope Laboratories, Inc.

Pentaerythritol tetrakis(3-mercaptopropionate) was purchased from Sigma-Aldrich. 1,3-Divinyltetramethyldisiloxane and 1,3,5 trimethoxybenzene were purchased from Fisher Scientific. Tris[2-(3-mercaptopropionyloxy)ethyl]isocyanurate was purchased from Alfa Chemistry. Pentaerythritol tetrakis(3-mercaptobutanonate), 1,3,5-tris[2-(3-mercaptobutanoyloxy)ethyl]-1,3,5-triazine-2,4,6-(1*H*,3*H*,5*H*)-trione, and 1,4-bis(3-mercaptobutyryloxy)butane also known as KarenzMT PE1, KarenzMT NR1, and KarenzMTBD1, respectively, were samples generously given to the laboratory by Showa Denko America, Inc.

All molecules, monomers, and solvents were used as received.

Procedures. *FTIR Characterization.* Samples were prepared by mechanically mixing NPPOC-TMG (2.5 wt % of the total solution for monofunctional experiments and 2.0 wt % for polymeric solutions) with the thiol and alkene which were present in a 1:1 functional group ratio. The sample mixture was deposited onto NaCl plates in a laminated configuration. A Nicolet 6700 FTIR with a vertical light cable was used for all FTIR experiments. The samples were placed in a chamber purged with dry air and then irradiated using a 365 nm UV light at 10 mW/cm^2 at an ambient temperature. A radiometer (model IL 1400A equipped with a GaAsP detector and a quartz diffuser) was used to measure the irradiation intensities. A series of scans taking spectra at a rate of 0.87 s/scan was used to monitor the alkene peak area (~3030−3100 cm^{-1}), and the thiol peak area (~2480−2520 cm^{-1}) in real time for conversion and kinetic analysis.

^{1}H NMR Conversion Studies. Conversion was determined by taking before and after proton spectra of reaction mixtures, monitoring the change in integration for an alkene peak between δ 6.4−6.8 and a thiol peak at δ 1.3−1.5 for the alkyl thiols and 1.7−1.8 for the mercaptopropionates. All proton NMR spectra were recorded on a Bruker Avance III 400 MHz spectrometer at 25 °C and are reported in ppm (δ) relative to internal tetramethylsilane (δ 0.0). All samples were diluted with deuterated chloroform.

The reaction mixtures were first prepared by dissolving the photobase, NPPOC-TMG (2.5 wt %) in the appropriate thiol and alkene mixture of a 1:1 functional group ratio. An initial NMR spectrum was recorded before the samples were injected into a glass slide−silicone rubber−glass slide sandwich in which the silicone had a hole punched through it. The samples were irradiated with 365 nm light at 10 mW/cm^2 on each side for a period of 5 min longer than it took to reach full conversion, as reported by FTIR. The sample was then removed from the sandwich and prepped for a final NMR spectrum. Each thiol and alkene mixture was prepared for a total of three different times, and three samples were taken from each solution for a total of nine trials.

Shelf Life Stability. Samples of 10.0 g mixtures of resins containing thiol and alkene monomers were prepared and then stored in amber glass vials at room temperature, with careful precautions taken against any exposure to UV radiation. Viscosity measurements were taken at various time points using a rheometer (TA Ares G2 4010-0778). The rheometer used 0.05 mL aliquots and measured viscosity with a 20 mm stainless steel parallel plate and 0.2 mm gap at a constant temperature of 22 °C. The sheer rate was ramped from 10 to 1000 s^{-1} over a period of 120 s.

■ RESULTS

Model Monofunctional Compound Studies. Despite significant progress on the understanding and implementation of the thiol-Michael addition reactions and step-growth polymerization strategies,[10,19−22] it is still unclear how the thiol substitution affects the kinetics and efficiency of the thiol-Michael addition reactions. To investigate thiol substitution effects, a kinetic study was conducted using monofunctional alkyl thiols and difunctional mercaptopropionates (with monofunctional alkenes) as model compounds. Ideally, the small molecule, monofunctional reactions are chemically nearly identical to those in a polymerization and lend great insights into the kinetic aspects without additional complicating factors associated with diffusion, polarity, and viscosity changes, all of which accompany the reaction during polymerization.[23] FTIR spectroscopy was used to observe how three different isomers of butane thiol, that is, *n*-butane thiol (NBT), SBT, and TBT, reacted under typical the thiol-Michael reaction conditions.

Three alkenes, with different reactivities in the thiol-Michael reactions, were selected. The more electron-deficient alkene typically has a faster kinetic rate, so comparing the alkenes in this experiment, the divinyl sulfone was the most reactive with all three thiols, followed by acrylate, and then fumarate, which additionally lends insights to differences between terminal and internal alkenes. Structures of these compounds are shown in Figure 2.

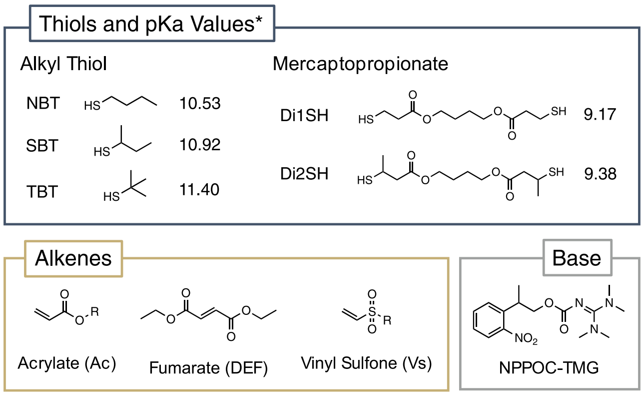

Figure 2. Structures of compounds used in monofunctional studies, including the monofunctional alkyl thiols (NBT, SBT, and TBT) and mercaptopropionates (Di1SH and Di2SH), the alkenes (Ac, DEF, and VS), and the photobase (NPPOC-TMG). The pK_as listed are reported from SciFinder.[24]

There is a difference in trend if one is looking at the alkyl thiols or looking at the mercaptopropionate. For the alkyl thiols, the increase in thiol substitution causes a decrease in the reaction rate across all three alkenes used. In the case of vinyl sulfone, the reaction rate decreased about 1.0 s^{-1} with each increase in substitution. The acrylate and the fumarate saw about a 50% decrease in rate from the primary to secondary thiol and the tertiary thiol reaction with either of these alkenes resulted in a very slow rate, less than 0.05 s^{-1} (Table 1). The final conversion between primary and secondary thiols of all alkenes and also the tertiary thiol reacting with the vinyl sulfone typically reached high conversions of 80% or higher. This was confirmed using IR and NMR spectroscopies (Table 1). The tertiary thiol reacting with either the acrylate or the fumarate suffered reduced conversions, as well as discrepancies between the thiol and acrylate conversion. The slightly elevated thiol conversion over the alkene is attributed to the slow nature of the reaction and long exposure time of UV light, possibly resulting in the self-initiation of the thiol and formation of disulfides (Figure 3).

For the mercaptopropionate, the secondary thiol actually reacted faster than the primary thiol for the acrylate and vinyl sulfone alkenes and at about the same rate for the fumarate (Figure 3). The secondary thiol was about 0.03 s^{-1} faster when reacting with the acrylate and 1.6 s^{-1} faster when reacting with the vinyl sulfone. Both primary and secondary thiols reached high conversions with the acrylate and vinyl sulfone alkenes; however, even though the rates were very similar, for the fumarate, the secondary thiol reaction had slightly lower conversions reported from the IR.

The differences in rate are attributed to the fact that alkyl thiols and mercaptopropionates have different rate-determining steps, as reported by Huang *et al.*[25] The more basic alkyl thiolate anion allows for increased nucleophilicity, resulting in a chain transfer rate-limiting step. In this case, the increased steric hindrance would slow the enolate deprotonating the thiol. The resulting trend is that the tertiary thiol is the slowest and the primary thiols are the fastest. However, for mercaptopropionates, the conjugate base has a lower nucleophilicity than that of the alkyl thiols and, additionally, they are more acidic and therefore have a more reactive chain transfer step. This means that mercaptopropionates have a propagation rate-limiting step, and in this step, the less stable thiolate anion is going to react faster—that is, the one with the higher pK_a. In this case, the primary thiol is slower than that in the secondary. In the case of fumarate, it is likely that the steric interactions from the additional methyl group of the secondary thiol and the internal alkene override the electronic differences, resulting in nearly similar rates.

Thiol-Michael Cross-linking Systems. The effect of the substitution of the thiol was further studied in polymer network-forming resins comprising either primary or secondary thiols because the tertiary thiol demonstrated poor reactivity and low reaction yields. Primary and secondary analogues with varying numbers of thiol functional groups of some of the more commonly used thiol monomers were selected.

The compounds selected were chosen based on the substitution and functionality of the thiol (Figure 4). As such, the effects of both the number of thiol functional groups and the degree of thiol substitution on the conversion and polymerization kinetics with either a difunctional or tetrafunctional alkene were investigated and compared.

From the results, several trends are seen in the data. As the thiol functionality increases for the primary thiol reacting with either a diene or a tetraene, the polymerization reaction rate increases. For the diene, the alkene reaction rate increased from 0.6 ± 0.4 to 0.9 ± 0.2 to 2.3 ± 0.6 s^{-1} for the difunctional, trifunctional, and tetrafunctional thiols, respectively. Similarly, for the tetraene, the rate increased from 0.15 ± 0.01 to 0.3 ± 0.1 to 1.2 ± 0.7 s^{-1} as the thiol functionality increased (Table 2). The opposite trend was observed for the reaction kinetic experiments with secondary thiols where the rates decreased with increasing thiol functionality. This behavior most likely is due to the fact that with higher substitution and higher functionality, the thiolate becomes less accessible, thus increasing the propagation step of the polymerization process. Interestingly, the secondary trifunctional thiol reacting with the tetraene had a reaction rate of 0.4 ± 0.3 s^{-1}, compared to the secondary tetrafunctional thiol

Table 1. Reaction Rates in (%/s) and Final Percent Conversions Found Using FTIR Analysis for the Acrylate (Ac), Vinyl Sulfone (VS), and Fumarate (DEF) Alkenes All with a 2.5 wt % Photoinitiator NPPOC-TMG Exposed to 365 nm at an Intensity of 10 mW/cm^2[a]

	rate (s^{-1})		IR final conversion (%)		NMR final conversion (%)	
	alkene	thiol	alkene	thiol	alkene	thiol
			acrylate (Ac)			
NBT	2.4 ± 0.2	2.2 ± 0.3	98 ± 8	92 ± 5	100 ± 0	92 ± 4
SBT	1.0 ± 0.2	0.9 ± 0.2	91 ± 8	90 ± 10	98 ± 1	97 ± 1
TBT	0.02 ± 0.00	0.04 ± 0.01	31 ± 4	47 ± 1	60 ± 10	50 ± 10
Di1SH	0.9 ± 0.2	0.8 ± 0.2	100 ± 2	94 ± 9	98 ± 2	95 ± 3
Di2SH	1.1 ± 0.1	1.2 ± 0.1	91 ± 3	100 ± 8	98 ± 2	95 ± 3
			vinyl sulfone (VS)			
NBT	2.9 ± 0.8	2.4 ± 0.2	100 ± 5	101 ± 5	100 ± 0	99 ± 1
SBT	2.0 ± 0.6	1.6 ± 0.3	100 ± 10	97 ± 4	100 ± 1	96 ± 1
TBT	0.9 ± 0.2	0.9 ± 0.2	80 ± 10	90 ± 10	95 ± 5	97 ± 4
Di1SH	1.1 ± 0.2	1.1 ± 0.2	94 ± 4	95 ± 3	99 ± 1	97 ± 2
Di2SH	2.8 ± 0.6	2.6 ± 0.3	98 ± 3	95 ± 5	100 ± 0	98 ± 2
			fumarate (DEF)			
NBT	0.5 ± 0.2	0.60 ± 0.2	93 ± 9	96 ± 9	99 ± 0	97 ± 1
SBT	0.32 ± 0.04	0.31 ± 0.03	87 ± 7	90 ± 6	93 ± 2	87 ± 2
TBT	0.03 ± 0.01	0.07 ± 0.04	22 ± 8	50 ± 10	40 ± 10	40 ± 20
Di1SH	0.59 ± 0.09	0.54 ± 0.08	93 ± 9	90 ± 10	94 ± 2	93 ± 1
Di2SH	0.7 ± 0.1	0.6 ± 0.1	79 ± 9	72 ± 9	98 ± 2	93 ± 7

[a] All reactions were completed at room temperature.

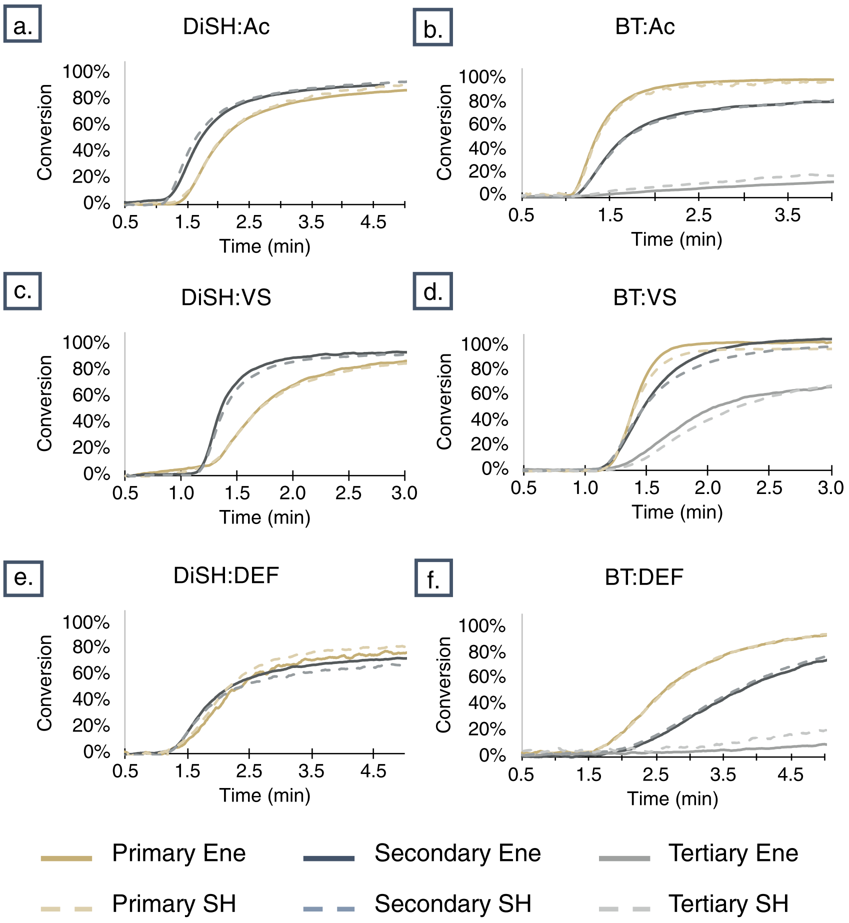

Figure 3. Alkene (solid) and thiol (dashed) conversion over time for reactions with acrylate (a,b), vinyl sulfone (c,d), and diethyl fumarate (e,f) with the propionate (DiSH) and alkyl (BT) thiols. All reactions were completed using a 1:1 functionality of thiols to alkenes, and resins contain 2.5 wt % NPPOC-TMG. Reactions proceeded using a 365 nm light to cleave the photo-protected base at 10 mW/cm^2 light intensity.

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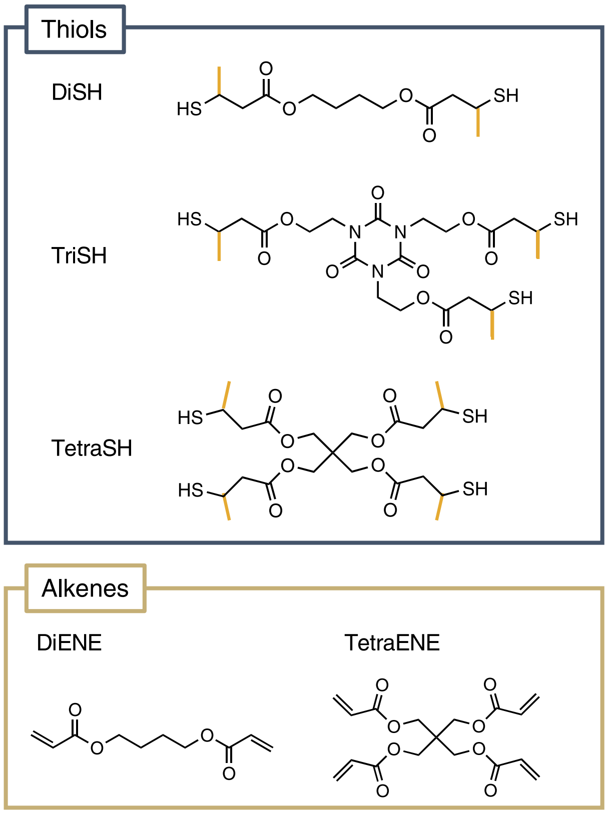

Figure 4. Structures of compounds used in polymerization kinetic studies including the primary thiols (1DiSH, 1TriSH, and 1TetraSH), the secondary thiols indicated by the methyl groups in yellow (2DiSH, 2TriSH, and 2TetraSH), and a difunctional (diene) and a tetrafunctional (tetraene) alkene. The photoinitiator used in all of these studies was the photobase NPPOC-TMG pictured in Figure 2.

reacting with the tetraene, which had a reaction rate of 0.7 ± 0.4 s^{-1}. As such, for secondary thiols, the trifunctional thiol ended up having the slowest rate. In addition, for the diene polymers, both substitution and functionality do not appear to have a pronounced effect on the final conversion of the polymer. However, for the tetraene reaction with the trifunctional and tetrafunctional thiols, the conversion was incomplete. This result is most likely due to acrylate homopolymerization because the final conversions for the alkenes were higher than those of the corresponding thiols. Moreover, the difunctional and tetrafunctional polymers had higher conversions than the trifunctional system, which is attributed to the rigid nature of the triazine−trione core slowing conversion through stiffening of the polymer chains and therefore limiting mobility. It is important to note that for all of the samples, they were all gelled and formed solid polymers prior to removal from the IR.

When comparing primary versus secondary thiols, the secondary thiol often reacts faster than the primary thiol, as seen with the DiSH/diene and DiSH/tetraene resins (Figure 5), but the differences in reactivities seem to diminish with increasing thiol functionality. The trifunctional thiol had similar rates between the primary and secondary thiols—the diene kinetic rate being 0.9 ± 0.2 to 1.0 ± 0.2 s^{-1} for the primary and secondary thiols, respectively, and the tetraene kinetic rate being 0.3 ± 0.1 to 0.4 ± 0.2 s^{-1} for the primary and secondary thiols, respectively. The TetraSH/diene resin found the primary thiol being faster (2.2 ± 0.5 s^{-1}) than the secondary thiol (1.0 ± 0.2 s^{-1}), and the TetraSH/tetraene resin showed comparable rates. This trend generally indicates that with lower average monomer functionality, the secondary thiols have a faster rate than the primary thiols. As the average monomer functionality increases, the primary thiol's rate increases, while the secondary thiol's rate decreases. This phenomenon may be due to mechanistic changes with changes in cross-link density. In less densely cross-linked or linear systems, that is, systems with a lower average monomer functionality, the inherent chemical reactivity largely controls the polymerization rate, whereas as the cross-link density

Table 2. Kinetic Rates (s^{-1}) and Final Percent Conversions of the Thiol-Michael Polymer Reactions Found Using FTIR Analysis for the Primary and Secondary Thiol Monomers (2.0 wt % Initiator, 365 nm, 10 mW/cm^2)[a]

	IR polymerization rates			
	primary (1°)		secondary (2°)	
	alkene rate (s^{-1})	thiol rate (s^{-1})	alkene rate (s^{-1})	thiol rate (s^{-1})
DiSH/diene	0.6 ± 0.4	0.6 ± 0.4	2.3 ± 0.4	2.3 ± 0.4
DiSH/tetraene	0.15 ± 0.01	*slow*	3.3 ± 1.4	1.0 ± 0.2
TriSH/diene	0.9 ± 0.2	0.9 ± 0.3	1.0 ± 0.2	1.0 ± 0.6
TriSH/tetraene	0.3 ± 0.1	0.1 ± 0.1	0.4 ± 0.2	0.4 ± 0.3
TetraSH/diene	2.3 ± 0.6	2.2 ± 0.5	1.0 ± 0.2	1.0 ± 0.2
TetraSH/tetraene	1.2 ± 0.7	0.7 ± 0.6	1.2 ± 0.1	0.7 ± 0.4
	IR conversion values			
	primary (1°)		secondary (2°)	
	alkene conversion (%)	thiol conversion (%)	alkene conversion (%)	thiol conversion (%)
DiSH/diene	99 ± 5	79 ± 9	96 ± 2	94 ± 1
DiSH/tetraene	85 ± 4	17 ± 3	96 ± 11	90 ± 4
TriSH/diene	96 ± 6	88 ± 15	94 ± 9	90 ± 20
TriSH/tetraene	80 ± 10	50 ± 10	72 ± 20	60 ± 20
TetraSH/diene	95 ± 4	98 ± 2	92 ± 4	90 ± 4
TetraH/tetraene	90 ± 20	40 ± 30	88 ± 8	70 ± 20

[a] All reactions were completed at room temperature. The term "*slow*" refers to the polymers that had less than 30% conversion over a minimum of 10 min.

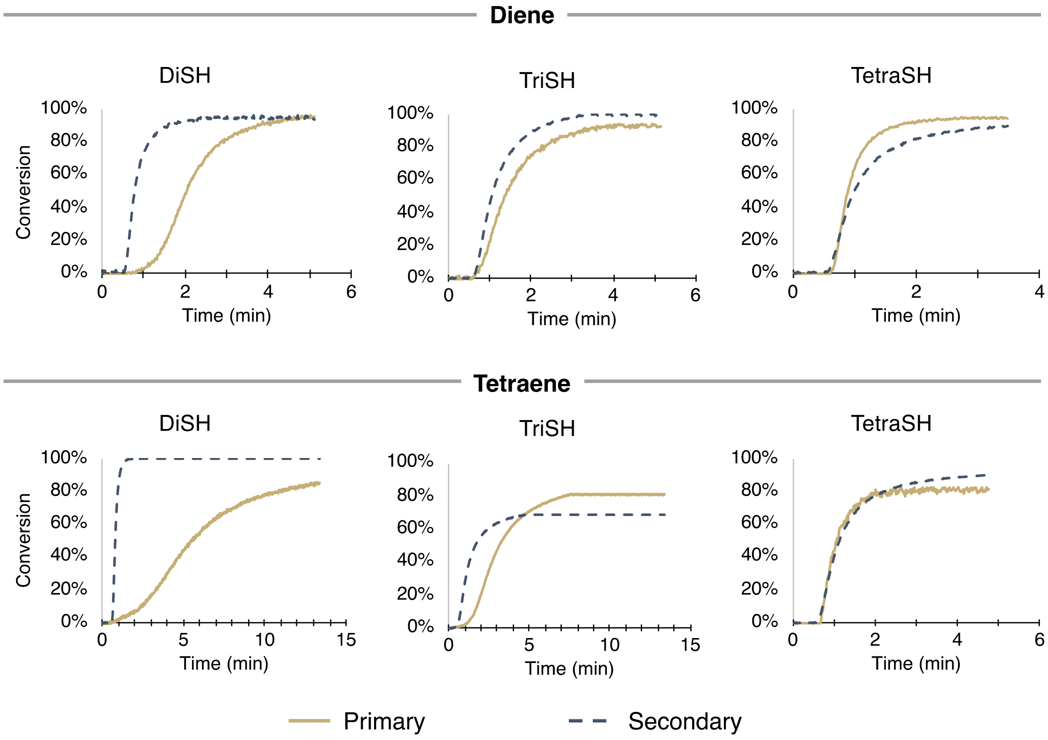

Figure 5. Alkene conversion as a function of time for reactions with the diene and tetraene alkenes and primary (solid line) and secondary (dashed line) thiols: DiSH (left), TriSH (Middle), and TetraSH (right). All reactions were completed using a 1:1 functionality of thiols to alkenes and contain 2.0 wt % NPPOC-TMG. Reactions were initiated using a 365 nm light to cleave the photo-protected base at 10 mW/cm^2 light intensity.

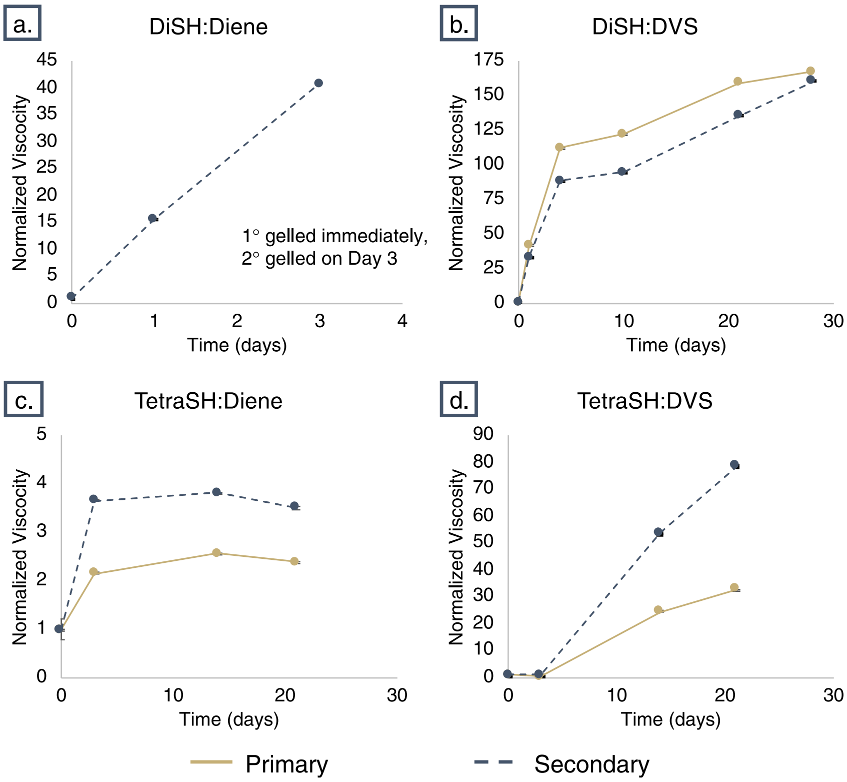

Figure 6. Rheological shelf life experiments for the primary (solid line) and secondary (dashed line) thiols when mixed with either diene or DVS alkenes. The primary DiSH and diene mixture gelled immediately, while the secondary resin gelled after day 3. The rest of the experiments were conducted for 28 days at room temperature. The resin mixtures were stored in amber vials in a box and only opened under yellow light. Experiments were performed in triplicate on three different samples, and the error bars are included here, albeit that they are often smaller than the symbol.

increases, mobility becomes more of a factor limiting the reaction rate.

Shelf Life Studies. The highly reactive thiol-Michael reaction is often prone to spontaneous self-initiation, thus limiting the shelf life of a premixed thiol and alkene resin. It has been reported that some alkenes in the thiol-Michael reactions, particularly those that are highly electron deficient such as maleimides, are not stable for long periods of time reacting spontaneously in short periods of time.[11] This instability could potentially be offset by using the Bronsted acids such as methanesulfonic acid, though this approach is often not viable as a long-term strategy.[26] Secondary thiols have been shown to increase the stability of radically polymerizable thiol−ene resins for long periods of time when compared to their primary counterparts, and in some cases, the secondary thiol and alkene resins remained ungelled for 3 months longer than the primary thiol and alkene resins.[16] Therefore, this work sought to determine if a similar effect is observed for thiol-Michael resins.

Accordingly, shelf life studies were completed using the rheometer to measure the viscosity of stoichiometric thiol and alkene resins over time. According to Figure 6, some resins were more stable with secondary thiols. When the primary DiSH was mixed with the diene, the resin gelled before any significant rheological data could be collected, while the corresponding secondary DiSH/diene resin lasted for 3 days before gelation (Figure 6a). Additionally, the secondary DiSH/DVS resin maintained a similar or potentially slightly lower viscosity over a 28 day time period than the primary DiSH/DVS resin (Figure 6b). It is interesting that this phenomenon occurred because the secondary DiSH thiol had a higher reaction rate than the primary DiSH thiol when mixed with the diene. The primary and secondary DiSH/DVS solution gelled after the 28th day.

Resins incorporating the TetraSH did not follow the same pattern. The primary TetraSH solutions maintained a lower viscosity than the secondary TetraSH for both the diene and DVS solutions, though it should be noted that all of these solutions gelled after the 21st day (Figure 6c,d) and are relatively similar in stability. This behavior is likely due to the fact that the secondary TetraSH thiol had a higher reaction rate with the diene than the primary TetraSH thiol.

The differences in trends between kinetic experiments and shelf life experiments are attributed to a number of different attributes, mainly to the fact that these two experiments are performed under drastically different conditions. Kinetic experiments are performed in small, milligram batches with intentional photoinitiation while shelf life experiments are conducted on a 10 g scale and left to spontaneously initiate. Kinetic experiments generally react to near-complete conversion, whereas shelf life experiments are left to sit in the dark, unexposed to an initiating light source. Therefore, differences in trends could be related to the rate of spontaneous initiation, the ability to terminate a small number of generated anions or as a result of the dramatic differences in the initiation rate. It is also possible that the shelf life mixtures proceed through a largely different reaction pathway altogether.

CONCLUSIONS

In monofunctional thiol-Michael addition systems comprising model thiol and -ene compounds, the changes in reaction rates of the thiol were due to both steric and electronic interactions. For alkyl thiols, which have a chain transfer rate-limiting step, steric interactions slowed the deprotonation of the thiol (1° > 2° > 3°). For propionates, which have a propagation limiting step, the thiol with the higher pK_a and thus more reactive thiol had the faster rate (2° > 1°), except in the case where steric interactions appeared to override the electronic effects, as seen with the internal alkene of the fumarate. Notably, the tertiary thiol showed slower rates and much lower conversions when compared to the primary and secondary thiols. Only primary and secondary thiols were studied in polymeric studies because of the significantly reduced rate in the tertiary thiols.

In polymeric systems, whether or not the primary thiol was faster than the secondary thiol was dependent on the functionality of the system. In systems where the combined monomer functionality was the lowest (*i.e.,* difunctional alkenes with difunctional thiols), the secondary thiol was faster than the primary thiol, and as the monomer functionality increased, the reaction rates of the two types of thiols became more comparable. In tetrafunctional thiol and alkene systems, the primary thiol had the faster reaction rate and the secondary thiol was slower.

In shelf stability assessments, for the DiSH systems, typically, the primary thiol was more unstable, but all of the solutions gelled within a month. In the TetraSH systems, the primary thiol generally maintained a lower viscosity over time, but these solutions also gelled within a month.

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Notes

The authors declare no competing financial interest.

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