Free Radical Polymerization of Caffeine-Containing Methacrylate Monomers

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ABSTRACT: The incorporation of acrylic functionality into caffeine enables the preparation of a vast array of novel thermoplastics and thermosets. A two-step derivatization provided a novel caffeine-containing methacrylate monomer capable of free radical polymerization. Copolymers of 2-ethylhexyl methacrylate and caffeine methacrylate (CMA) allowed for a systematic study of the effect of covalently bound caffeine on polymer properties. ¹H NMR and UV-vis spectroscopy confirmed caffeine incorporation at 5 and 13 mol %, and SEC revealed the formation of high molecular weight (co)polymers (>40,000 g/mol). CMA incorporation resulted in a multistep degradation profile with initial mass loss closely correlating to caffeine content. Differential scanning calorimetry, rheological, and thermomechanical analysis demonstrated that relatively low levels of CMA increased the glass transition temperature, resulting in higher moduli and elucidating the benefits of incorporating caffeine into polymers. © 2015 Wiley Periodicals, Inc. J. Polym. Sci., Part A: Polym. Chem. **2015**, *53*, 2829–2837

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INTRODUCTION Nature plays an inspirational role in polymer science, providing designs and templates for complex functions and properties as well as offering an abundance of renewable resources.^{1,2} Research dealing with the incorporation of renewable or bio-based compounds into polymeric materials surged as environmental concerns and efforts toward sustainability increased.^{3–5} Consideration of the effect of synthetic materials on the environment is pervasive in both academic and industrial laboratories.^{6,7} One means to achieve the goals of green chemistry includes the synthesis of functional materials solely comprised of bioderived compounds, for example, poly(lactic acid).⁸ Alternatively, introducing small amounts of renewable compounds into a polymeric material offers a route to achieve increased sustainability while either attempting to maintain the original material properties or further tuning properties.⁹ Monomers derived from corn feedstock, particularly sugar-based alcohols and acids such as 1,4:3,6-dianhydrohexitols and succinic acid found great success as they readily possess functional groups for derivatization and polymerization.^{10–13}

Caffeine, a well-known stimulant present in coffee and chocolate, belongs to a class of molecules referred to as xanthines.^{14,15} Other xanthine derivatives with a similar chemical structure include theophylline and theobromine,

depicted in Figure 1 below. Encapsulation, delivery, molecularly imprinted polymers (MIPs), and the effect on oxygen permeability of polyesters represent recent research topics for caffeine.¹⁶⁻²¹ For example, Bowyer and coworkers²⁰ synthesized caffeine and theophylline MIPs using both microwave and thermally induced polymerization. The polymerization technique affected the rebinding affinity; microwave MIPs exhibited higher dissociation constants than the thermally induced MIPs. Caffeine nearly doubled the oxygen barrier as an additive in 500-mL poly(ethylene terephthalate) bottles.¹⁶ Oxygen transmission rates decreased from 0.046 cc/pkg/day for a bottle without caffeine to 0.0306 and 0.0261 cc/pkg/day with only 3 and 5 wt % caffeine incorporation respectively. The patent invokes an antiplasticization effect of caffeine, however, the origin of this dramatic increase in gas barrier has remained unexplored.

Natural polymers, chemicals, and chemical processes exhibit a high level of structural complexity, bestowing intricate functions and properties.²² Many strive toward mimicking natural design when synthesizing polymers, such as the ability of a gecko to walk on walls, the color-changing capabilities of a chameleon, and our own biological code deoxyribonucleic acid (DNA).²³⁻²⁵ Polymerizable functional groups or reactive sites are essential for chemical derivatization and polymerization. Unlike adenine, caffeine does not

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FIGURE 1 Chemical structures of caffeine (with atoms numbered for reference), theophylline, and theobromine.

contain a readily reactive functional group such as an amine. This aromatic heterocycle, which contains hydrogen bond accepting carbonyls, noncovalently interacts with receptors and remains unaltered chemically.²⁶ In the early 1970's, Salomon and coworkers^{27,28} reported the ability to incorporate hydroxyl functionality at the 8-position of caffeine, adenine, adenosine, guanosine, and 2'-deoxyguanosine. Figure 2 depicts the chemical similarity between adenosine, caffeine, and the nucleobase adenine. More recently, Alami et al.²⁹ alkenylated at the 8-position of caffeine with a Pd/Cu catalyzed coupling reaction. On careful analysis of the literature, caffeine is present in many publications; however, derivatizing and covalently incorporating caffeine into a copolymer remains unexplored.

In this manuscript, we describe for the first time the synthesis, polymerization, and physical characterization of caffeinecontaining copolymers. A novel caffeine methacrylate (CMA) monomer, which is available from a photoreaction to introduce an alcohol and subsequent acid chloride reaction, readily underwent free radical copolymerization with 2ethylhexyl methacrylate (EHMA). Poly(EHMA) served as a control, and incorporation of various amounts of CMA allowed for an investigation of the effect of caffeine on acrylic copolymer properties. ¹H NMR spectroscopy confirmed CMA incorporation, and CMA altered the thermal, thermomechanical, rheological, and UV-vis absorbance properties. These copolymers demonstrate the capability and feasibility of incorporating the renewable resource caffeine into acrylic polymers and elucidate the influence of the heterocyclic structure on polymer properties.

EXPERIMENTAL

Materials

Caffeine (99%), methacryloyl chloride (MAC; 97%), Luperox[®] DI (di-*tert*-butyl peroxide, DBP; 98%), and dioxane (spectrophotometric grade, 99+%) were obtained from Sigma Aldrich and used as received. Triethylamine (TEA; Sigma Aldrich; \geq 99%) was distilled from calcium hydride prior to use. 2-ethylhexyl methacrylate (EHMA; Sigma Aldrich; 98%) was eluted through an aluminum oxide column to remove inhibitor prior to use. 4,4'-Azobis(4-cyanopentanoic acid) (V-501; Sigma Aldrich; \geq 98%) was recrystallized from ethanol prior to use. Chloroform (CHCl₃), methanol (MeOH), isopropanol (IPA), and tetrahydrofuran (THF; stabilized with 0.025% BHT) were purchased from Spectrum Chemicals and used as received. Ethanol (EtOH) was obtained from Decon Laboratories, and used as received. Dry dichloromethane (DCM) was obtained upon treatment with a Innovative Technology Puresolve solvent system.

Analytical Methods

¹H NMR spectroscopy was performed on a Varian Inova or Agilent U4-DD2 400 MHz spectrometer with samples prepared in deuterated chloroform (CDCl₃) or deuterated dimethyl sulfoxide (DMSO_{d6}). Dynamic light scattering (DLS) using a Malvern Zetasizer Nano ZS at 25 °C provided the hydrodynamic diameter of the copolymers in THF. The (co)polymer solutions were filtered through a 0.45 μ m PTFE syringe filter prior to analysis and the results are an average of three runs. Size exclusion chromatography (SEC) was performed in THF on a Waters 515 HPLC pump equipped with a Waters 717plus autosampler. Samples were analyzed at a concentration of 1 mg/mL in THF through a series of three Polymer Laboratories PLgel 5 μ m MIXED-C columns at a flow rate of 1 mL/min and results obtained using a Waters 2414 refractive index (RI) detector and Wyatt Technology Corporation Mini-dawn MALLS detector. Absolute molecular weight data was obtained using the dn/dc value for poly(-EHMA) in THF determined offline with a Wyatt Technology Optilab[®] T-rEX refractive index detector. Thermal transitions of the (co)polymers were obtained using a TA Instruments Q50 TGA and TA Instruments Q1000 DSC affording degradation temperatures (T_d) and glass transition temperatures $(T_{\rm g})$, respectively. A heating rate of 10 °C/min was used for the TGA and a heat/cool/heat method of 10 °C/min from room temperature to 100 °C, 10 °C/min from 100 to -80 °C, and 10 °C/min from -80 to 100 °C was used for the DSC and thermograms reported from the second heating, ensuring all samples had identical thermal history.

Photoreactions

Photoreactions were conducted in an Ace Glass photochemical safety cabinet using a 24.4475 cm 450 W ultraviolet (UV) immersion lamp connected to a 120 V, 60 Hz, 450 W UV power supply. The UV immersion lamp was placed inside a water-cooled condenser which fit inside a Pyrex[®] apparatus equipped with a N₂ inlet and outlet.

Thermomechanical Analysis

Dynamic mechanical analysis (DMA) was performed on a TA Instruments Q800 DMA in tension mode conducted at a frequency of 1 Hz. Samples were equilibrated at -50 °C, held



FIGURE 2 Chemical structures of adenosine, caffeine, and adenine (with atoms numbered for reference).

for 5 min, and then heated at a rate of 3 $^{\circ}C/min$ until flow. Polymer films were solution-cast from $CHCl_3$ onto a Mylar sheet, maintained at 20 $^{\circ}C$ overnight, placed in a vacuum oven at ca. 50 $^{\circ}C$ for at least 7.5 h, and finally vacuum was closed and the film remained at 50 $^{\circ}C$ for at least 22 h.

Ultraviolet-Visible Spectroscopy

A Ocean Optics Inc. USB 2000 spectrometer coupled to a CUV sample holder providing a 1 cm pathlength enabled ultraviolet-visible (UV-Vis) spectroscopy. An Analytical Inst. Systems Model DT 1000CE UV light source provided a wavelength range of 190–850 nm. All solutions were prepared in dioxane and measurements occurred in a quartz cuvette. 10^{-4} M caffeine control solutions and 2.6(10^{-5}) M caffeine-containing copolymer solutions (normalized to caffeine content) were suitable for quantitative absorbance measurements.

Melt Rheology

A TA Instruments Discovery HR-2 hybrid rheometer equipped with an environmental test chamber (ETC) provided time-temperature superposition (TTSP) melt rheology data. The measurements were performed using an 8-mm parallel plate steel geometry. An amplitude sweep was conducted first to ensure frequency measurements were performed at a strain within the viscoelastic regime of the material, and master curves were shifted to a reference temperature ($T_{\rm ref}$) of 30 °C. Complex viscosity data was also reported for all samples at 30 °C.

Synthesis of Hydroxyl Functionalized Caffeine

The procedure involved an adaptation of a previously reported procedure²⁷ and the MeOH, EtOH, and IPA caffeine derivatives were all prepared in a similar manner. The photoreactions were conducted in the setup described above. For example, the synthesis of the MeOH derivative, 8-(hydroxymethyl)-1,3,7-trimethyl-3,7-dihydro-1*H*-purine-2,6dione, follows. 10.0 g of caffeine, 87 mL of reverse osmosis (RO) water, and 350 mL of MeOH were added to the photoreactor glassware with a magnetic stir bar. 25 mL of DBP was then added to the reaction and a 15 min N₂ purge with stirring was allowed prior to UV irradiation. Upon irradiation, aliquots were extracted to monitor the progress of the reaction. Excess reagents were removed using a rotary evaporator and the crude mixture was dried in a vacuum oven (\sim 50 mmHg) at about 90 °C overnight. The crude reaction mixture was used in the subsequent acid chloride reaction; however, isolation of the compound was possible using silica gel chromatography. The crude reaction mixture was dissolved in 1:1 CHCl₃:MeOH, loaded onto the column and eluted with a 9:1 CHCl₃:MeOH solvent mixture. Prior to running the column, thin layer chromatography (TLC) was performed to ensure good separation. Using the aforementioned solvent system, caffeine exhibited an $R_{\rm f}$ value of 0.46 and the product exhibited an $R_{\rm f}$ value of 0.23. After collecting the product from the column, a rotary evaporator removed the solvent and the product was dried in a vacuum oven at ca. 40 °C. The isolated product (93% pure via NMR) was a white solid. HRMS: calcd for C9H12N4O3, 224.09; found,

224.09. ¹H NMR (400 MHz, DMSO- d_6 , δ): 3.90 (s, 3H, $-N-CH_3$), 3.39 (s, 3H, $-N-CH_3$), 3.20 (s, 3H, $-N-CH_3$), 4.57 (d, 2H, $-CH_2-$), 5.64 (t, 1H, -OH).

8-(1-Hydroxyethyl) – 1,3,7-Trimethyl-3,7-Dihydro-1*H*-Purine-2,6-Dione (EtOH Derivative). HRMS: calcd for C₁₀H₁₄N₄O₃, 238.11; found, 238.05. ¹H NMR (400 MHz, CDCl₃, *δ*): 3.95 (s, 3H, -N-CH₃), 3.49 (s, 3H, -N-CH₃), 3.33 (s, 3H, -N-CH₃), 4.94 (q, 1H, -CH-), 1.58 (d, 3H, -CH₃-), 2.85 (br, -OH).

8-(2-Hydroxypropan-2-yl) – 1,3,7-Trimethyl-3,7-Dihydro-1*H*-Purine-2,6-Dione (IPA Derivative, Crude). ¹H NMR (400 MHz, CDCl₃, δ): 4.10 (s, 3H, —N—CH₃), 3.43 (s, 3H, —N—CH₃), 3.27 (s, 3H, —N—CH₃), 1.62 (s, 6H, — (CH₃)₂), 2.72 (br, —OH).

Synthesis of Caffeine Methacrylate

Methacrylates were synthesized from both the MeOH and EtOH caffeine derivatives. Starting from the MeOH caffeine derivative, the following procedure describes the synthesis of (1,3,7-trimethyl-2,6-dioxo-2,3,6,7-tetrahydro-1*H*-purin-8-yl) methyl methacrylate (CMA). Dry DCM was added to the crude hydroxyl functionalized caffeine reaction mixture. The dissolved mixture in DCM was cannulated into a dry roundbottomed flask equipped with a magnetic stir bar. Using dry syringe techniques, TEA (0.1 mol equivalent excess compared to MAC) was added to the reaction and the contents were stirred in an ice bath. MAC was added to the reaction and the reaction was allowed to proceed, slowly warming up to room temperature with stirring overnight. A rotary evaporator removed excess reagents. Conventional free-radical polymerization was performed on the crude reaction mixture; however, dissolving the crude mixture in 20:1 CHCl₃:MeOH and eluting with 2:1 CHCl₃:acetone on a silica gel column allowed for CMA isolation. After collecting the appropriate fractions from the column, rotary evaporation removed the solvent and the product was dried in a vacuum oven at 50 °C overnight. HRMS: calcd for C₁₃H₁₆N₄O₄, 292.12; found, 292.12. ¹H NMR (400 MHz, CDCl₃, δ): 4.03 (s, 3H, -N-CH₃), 3.57 (s, 3H, -N-CH₃), 3.40 (s, 3H, -N-CH₃), 5.27 (s, 2H, -CH₂-), 6.16 (s, 1H, -H), 5.65 (t, 1H, -H), 1.95 (s, 3H, -C-CH₃).

1-(1,3,7-trimethyl-2,6-dioxo-2,3,6,7-tetrahydro-1*H*-purin-8-yl)ethyl methacrylate (from EtOH caffeine derivative). HRMS: calcd for C₁₄H₁₈N₄O₄, 306.13; found, 306.13. ¹H NMR (400 MHz, CDCl₃, δ): 4.01 (s, 3H, $-N-CH_3$), 3.56 (s, 3H, $-N-CH_3$), 3.38 (s, 3H, $-N-CH_3$), 6.02 (q, 1H, -CH-), 1.73 (d, 3H, $-C-CH_3$), 6.15 (t, 1H, -H), 5.63 (t, 1H, -H), 1.94 (t, 3H, $-C-CH_3$).

Free Radical Copolymerization of (1,3,7-Trimethyl-2,6-Dioxo-2,3,6,7-Tetrahydro-1H-Purin-8-yl)Methyl Methacrylate (CMA)

Conventional free radical polymerization afforded poly(ethylhexyl methacrylate) (poly(EHMA)) and caffeine-containing copolymers. All polymerizations were conducted in dioxane at 10% solids using 4,4'-azobis(4-cyanopentanoic acid) (V-501) as the free radical initiator (0.67 mol % for EHMA and 1.0 mol % for the copolymerizations). The reagents were added to a single-neck, round-bottomed, flask equipped with a magnetic stir bar, sparged with an inert gas, and then





SCHEME 1 Synthesis of hydroxyl-functionalized caffeine using a peroxide-initiated photoreaction.

allowed to react for approximately 24 h at 70 °C. Polymers were isolated upon precipitation into MeOH for poly(EHMA) and poly(EHMA₉₅-co-CMA₅), 80:20 MeOH:H₂O for poly(-EHMA₈₇-co-CMA₁₃); all products were filtered and dried in vacuo at 50 °C overnight.

RESULTS AND DISCUSSION

Synthesis and Copolymerization of Caffeine-Containing Methacrylate

Caffeine lacks functional groups capable of undergoing polymerization, thus chemical modification was necessary to achieve a caffeine-based monomer. Previous literature reported the methodology to introduce hydroxyl functionality at the 8-position of a variety of purine derivatives using a peroxide-initiated photoreaction between the purine and alcohol.²⁷ This reaction served as a first step, placing the reactive hydroxyl group on caffeine allowing for further derivatization to a methacrylate. Scheme 1 depicts the photoreaction and conditions used to synthesize the methanol caffeine derivative. The bond created in the photoreaction forms at the carbon directly adjacent to the hydroxyl group, therefore, different alcohols (methanol, ethanol, and isopropanol) afforded caffeine with a primary, secondary, and tertiary hydroxyl, respectively.

Figure 3 depicts the chemical structures and caffeine conversion as a function of exposure time for the three hydroxylfunctionalized caffeine derivatives. Caffeine conversion plateaued at 30% for each reaction despite the stability differ-



FIGURE 3 Photoreaction kinetics of caffeine with various alcohols as a function of time, determined using ¹H NMR spectroscopy, with primary (methanol), secondary (ethanol), and tertiary (isopropanol) radicals showing the independence of radical intermediate stability.



SCHEME 2 Synthesis of caffeine methacrylate (CMA) monomer.

ence between the three carbon radical intermediates $(1^{\circ} < 2^{\circ} < 3^{\circ})$. Murgida et al.³⁰ studied the photoreaction of caffeine, theophylline, and theobromine (Fig. 1) initiated with benzophenone. The proposed mechanism included a caffeine radical intermediate formed upon reaction of caffeine with the alcohol-based radical. The final product, hydroxylfunctionalized caffeine, ultimately formed from coupling of the radical intermediate of caffeine with either the alcoholbased radical or the benzophenone radical. Two routes prohibit the necessary caffeine radical intermediate: (1) combination of two alcohol-based radicals, and (2) combination of the photoinitiator radical with an alcohol-based radical. The molar excess of alcohol to both caffeine and peroxide in our reaction (173:1:6, respectively, for the MeOH derivative) favors alcohol-based radical combination/termination, presumably eliminating the effect of radical stability on caffeine intermediate formation, resulting in similar conversion for each reaction.

Placing the hydroxyl group on caffeine provided a reactive chemical site for further derivatization to a polymerizable methacrylate. A commonly employed reaction with methacryloyl chloride (MAC), as depicted in Scheme 2, provided a caffeine methacrylate (CMA) monomer.^{31,32} This second and final reaction in the monomer synthesis succeeded on the crude photoreaction mixtures, eliminating challenging isolation and purification steps. Supporting Information Figure S1 displays the ¹H NMR spectrum for CMA. 2-ethylhexyl methacrylate (EHMA), which is a well-studied monomer providing a low glass transition temperature (T_{σ}) , served as a comonomer to observe the influence of caffeine on thermomechanical properties.^{33–35} Conventional free radical copolymerization in dioxane of commercially available EHMA, CMA, and V-501 as a radical initiator, as represented in Scheme 3, generated copolymers containing covalently bound caffeine. Varying feed ratios of CMA to EHMA afforded a series of caffeinecontaining copolymers.

Structural Confirmation and Molecular Weight Analysis of Poly(EHMA_x-co-CMA_y)

Copolymerization proceeded on crude CMA to expedite synthesis and eliminate unnecessary solvent and waste from



SCHEME 3 Synthesis of caffeine-containing copolymers using conventional free radical polymerization.



FIGURE 4 Structural confirmation of $poly(EHMA_{95}$ -*co*-CMA₅) using ¹H NMR spectroscopy. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

workup procedures. This strategy prevented a determination of an accurate CMA feed ratio, therefore, NMR after polymer purification provided actual mol % CMA incorporation. Figure 4 depicts the ¹H NMR spectra of poly(EHMA₉₅-*co*-CMA₅). The region below 2 ppm corresponds to the backbone peaks and pendant alkyls on EHMA; however, integration of the distinct resonances for the three methyl groups on caffeine and the methylene adjacent to the ester for each monomer quantified mol % CMA. Purified control poly(EHMA) and CMA copolymers containing 5 and 13 mol % CMA (using integrations from resonance *a* and *d* in Fig. 4) allowed for an investigation of the impact of CMA on polymeric properties. Precipitation revealed an initial solubility difference; poly(EHMA₈₇-*co*-CMA₁₃) required an 80:20 MeOH:H₂O mixture as opposed to 100% MeOH for poly(EHMA) and poly(EHMA₉₅-*co*-CMA₅).



FIGURE 5 Normalized absorbance spectra for CMA-containing copolymers, including a caffeine control in dioxane showing a distinct red shift when caffeine is bound to the polymer backbone.

UV-Vis spectroscopy is a common analytical tool for evaluating conjugated molecules and polymers.^{36,37} Researchers utilized UV-Vis measurements to quantify and detect caffeine for various applications including determining the concentration in coffee and investigating mutagenic activity.38-40 Figure 5 displays the UV-Vis absorption spectra for caffeine, poly(EHMA95co-CMA₅), and poly(EHMA₈₇-co-CMA₁₃), confirming successful caffeine incorporation. Neat caffeine exhibited a maximum wavelength (λ_{max}) of 276 nm while poly(EHMA₉₅-co-CMA₅) and poly(EHMA₈₇-co-CMA₁₃) revealed similar elevated λ_{max} values of 282 nm and 283 nm, respectively. Increased conjugation enhances the stability of the π^* state, which simultaneously decreases the energy required for the transition ultimately increasing the wavelength of absorption.^{36,37} Therefore, the additional π bond and resonance present in the CMA-containing copolymers from the ester could account for the observed bathochromic shift.



FIGURE 6 Light scattering SEC chromatograms of poly(EHMA) control and caffeine-containing copolymers.

TABLE 1	Molecular	Weight and	Thermal	Degradation	of
Caffeine-	Containing	Copolymers	6		

Mol % CMAª	Wt % CMA	<i>M</i> _w (Kg/mol) ^b	PDI ^b	T _{d1,onset} (°C) ^c	Wt. Loss _{d1} (%) ^c	T _{dfinal,onset} (°C) ^c
0	0	99.2	2.13	269	N.D.	N.D.
5	7	78.5	1.89	195	10	313
13	18	40.1	2.12	194	13	315

^a Calculated from ¹H NMR.

 $^{\rm b}$ Absolute molecular weight data obtained from THF SEC at 40 $^{\circ}\text{C}$ using dn/dc = 0.088.

 $^{\rm c}$ TA Instruments Q50 thermogravimetric analyzer (TGA) heating at 10 $^{\rm o}C/min$

N.D. not detected

Size exclusion chromatography (SEC) in THF provided absolute molecular weight analysis of poly(EHMA), poly(EHMA₉₅*co*-CMA₅), and poly(EHMA₈₇-*co*-CMA₁₃). Figure 6 depicts the light scattering (LS) traces and Table 1 displays the corresponding weight-average molecular weight (M_w) and polydispersity index (PDI) for each copolymer. Offline determination of the refractive index increment, dn/dc, for poly(EHMA) afforded absolute molecular weight. Using the dn/dc value addressed the chemical dissimilarity between the CMAcontaining series and the polystyrene chromatography columns; however, it is important to emphasize that the poly(-EHMA) dn/dc generated the molecular weight data for all three (co)polymers in the series. A separate determination of the dn/dc value for each copolymer composition would minimize the effect of compositional differences on the results.

The three LS traces in Figure 6 show poly(EHMA) eluting first corresponding to the highest $M_{\rm w}$ of 99.2 kg/mol (Table 1). Although lower, both poly(EHMA₉₅-co-CMA₅) and poly(-EHMA₈₇-co-CMA₁₃) exhibited suitable M_{ws} for conventional free radical polymerization of 78.5 kg/mol and 40.1 kg/mol, respectively. A higher concentration of V-501 initiated the 5 and 13 mol % CMA copolymers compared to the poly(-EHMA) control. Since polymerization rate scales according to the square root of initiator concentration, the increased V-501 concentration lowers the final attainable polymer molecular weight and presumably contributed to the observed decreased M_w⁴¹ Poly(EHMA) and poly(EHMA₉₅-co-CMA₅) displayed monomodal LS traces, whereas poly(EHMA₈₇-co-CMA₁₃) contained a high molecular weight shoulder and slight low molecular weight shoulder. This could originate from the isolation procedure and/or poor THF dissolution during chromatography for this particular copolymer composition. Dynamic light scattering (DLS) in THF of the (co)polymers showed monomodal hydrodynamic diameter distributions (99.9 % of mean volume) of 12 ± 5 nm, 9 ± 3 nm, and 8 ± 2 nm for poly(EHMA), poly(EHMA₉₅-co-CMA₅), and poly(EHMA₈₇-co-CMA₁₃), respectively. These results provided evidence for good solubility in THF to ensure reliable SEC data. In lieu of the high molecular weight shoulder present in poly(EHMA₈₇-co-CMA₁₃), DLS also specified hydrodynamic diameter as a function of intensity. An

aggregation peak near 100 nm increased with increasing CMA content from 7% for poly(EHMA) to 30 and 49% for poly(EHMA₉₅-*co*-CMA₅) and poly(EHMA₈₇-*co*-CMA₁₃), respectively. This aggregation could account for the observed shoulder in the poly(EHMA₈₇-*co*-CMA₁₃) SEC trace. Supporting Information Figure S2 displays the hydrodynamic diameters for the (co)polymers as a function of mean volume % (**a**) and mean intensity % (**b**).

Thermal, Thermomechanical, and Rheological Characterization of Caffeine-Containing Copolymers

Thermogravimetric analysis (TGA) provided weight loss as a function of temperature in a N2 atmosphere for the (co)polymer series. Poly(EHMA) displayed a one-step degradation occurring at 228 °C while both poly(EHMA₉₅-co-CMA₅) and poly(EHMA₈₇-co-CMA₁₃) displayed multistep degradation profiles. Figure 7 depicts the decomposition curves and Table 1 specifies the degradation temperatures (T_d) and corresponding % weight loss. CMA-containing copolymers displayed an initial degradation lower than poly(EHMA), however, the largest degradation step of the copolymers increased \sim 50 °C compared to poly(EHMA). The final degradation temperature increased from 269 °C for poly(EHMA) to 313 and 315 °C for poly(EHMA₉₅-co-CMA₅) and poly(-EHMA₈₇-co-CMA₁₃), respectively. Additionally, the absence of early weight loss suggested the absence of volatile byproducts.

Interestingly, the initial wt. loss in poly(EHMA₉₅-*co*-CMA₅) and poly(EHMA₈₇-*co*-CMA₁₃) closely correlated to the loss of pendant caffeine. Beta hydrogen elimination is a commonly reported degradation route for methacrylates with pendant side chains or groups.^{42–44} CMA, however, does not contain any beta hydrogens eliminating the common route as a possible mechanism for caffeine loss. Fodor et al.⁴⁵ extensively researched the thermal decomposition of poly(*N*-vinylimidazole) using pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS). This highly sensitive analytical technique identified 10 different small molecule byproducts, one of them



FIGURE 7 Two-step thermal degradation profile of caffeinecontaining copolymers.



FIGURE 8 Proposed thermal degradation route of caffeinecontaining copolymers resulting in the loss of free caffeine. (Reproduced from Ref. 51 with permission from American Chemical Society).

being imidazole. Figure 8 depicts the proposed mechanism (left) constructed to support imidazole as a decomposition product. As discussed above, the photoreaction in the first step of CMA synthesis occurs through a radical intermediate at the same position on caffeine in which the proposed degradation mechanism occurs. With the propensity of caffeine to lose a hydrogen at the same attachment point, the right side of Figure 8 proposes a mechanism of side group elimination and subsequent hydrogen abstraction to explain the observed caffeine loss.

Differential scanning calorimetry (DSC) revealed a broad glass transition temperature for poly(EHMA), poly(EHMA₉₅*co*-CMA₅) and poly(EHMA₈₇-*co*-CMA₁₃), visible in Figure 9. Although difficult to assign an exact value due to the breadth of the transition, the observed $T_{\rm g}$ of poly(EHMA) corresponded well with the literature value of ~ -10 °C.³³ Incorporating caffeine increased the $T_{\rm g}$ of the polymers, visible



FIGURE 9 DSC shows broad T_g 's for the copolymers, trending upward with increasing CMA content.



FIGURE 10 Melt rheology exhibits higher moduli with increasing CMA content. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

from the plateau of the step-wise $T_{\rm g}$ shifting to the right for poly(EHMA95-co-CMA5) and higher for poly(EHMA87-co-CMA₁₃). The lack of any endothermic transitions indicated amorphous (co)polymers, and a single $T_{\rm g}$ suggested random copolymerization of the two methacrylates without microphase-separation. Placing hydrogen bonding sites pendant to the polymer backbone, Zhang et al.⁴⁶ observed highly ordered lamellar morphologies. Cheng et al.47 also observed H-bonding driven self-assembly upon synthesizing poly(acrylates) containing 7 mol % of an adenine-containing acrylate. Surprisingly, polymerizing a thymine-containing acrylate in concentrations up to 30 mol % incorporation did not exhibit any self-assembly. Caffeine does not hydrogen bond with itself, however, the aromatic structure is prone to π - π stacking.48-50 It is proposed that placing the caffeine pendant group further from the backbone will increase mobility, enabling the aromatic groups to π - π stack and potentially resulting in a distinct caffeine-rich phase. Additionally, increasing



FIGURE 11 Complex viscosity of poly(EHMA) and caffeinecontaining copolymers at 30 °C.



FIGURE 12 Thermomechanical analysis of 5 mol % CMA copolymer, showing an increased and extended glassy modulus compared to poly(EHMA) control.

CMA content will promote π - π stacking through a proximity effect.

Time-temperature superposition (TTSP) melt rheology and dynamic mechanical analysis (DMA) further investigated the effect of caffeine on thermal properties. Figure 10 displays the master curves, obtained using a 30 °C reference temperature (T_{ref}) , for the (co)polymer series. All polymers adhered to TTSP, which provided a broad range of rheological behavior over angular frequencies of 10^{-6} to $\sim 10^4$ rad/s. The crossover of the storage (G') and loss (G") moduli (G' = G") occurred in each material and shifted to lower frequencies with increasing CMA.⁵¹ Modulus also increased with increasing caffeine content. Contrary to the SEC results discussed previously where poly(EHMA) exhibited the highest $M_{\rm n}$, a shift of the crossover point to lower frequencies often indicates higher molecular weight.52 The shifted crossover point combined with the enhanced modulus suggested caffeine pendant groups increased chain stiffness. Similarly complex viscosity, depicted in Figure 11, followed an increasing trend with CMA incorporation. Complex viscosity often scales with molecular weight, thus these results further supported that pendant caffeine functional groups largely influenced chain stiffness.

All three (co)polymers formed films with solution casting from chloroform. Figure 12 shows the DMA curves of poly(-EHMA) and poly(EHMA₉₅-*co*-CMA₅) obtained from their respective films. Poly(EHMA₈₇-*co*-CMA₁₃) formed a film, however, films were glassy at room temperature, unlike the other two samples, and shattered while attempting to obtain a rectangular piece for thermomechanical testing. The stiffer, glassy, nature of poly(EHMA₈₇-*co*-CMA₁₃) correlated well to TTSP and viscosity data, demonstrating the influence of the caffeine pendant group on properties. Poly(EHMA) and poly(EHMA₉₅-*co*-CMA₅) exhibited DMA traces expected of amorphous materials; beginning with a glassy modulus at low temperatures and proceeding through a single transition (T_g) leading to flow. As observed in DSC, poly(EHMA₉₅-*co*-CMA₅) exhibited a slightly higher $T_{\rm g}$ than poly(EHMA), with a tan delta maximum occurring at 55 and 49 °C, respectively. Additionally, a higher storage modulus with CMA was consistent.

CONCLUSIONS

The successful synthesis and polymerization of a novel caffeine-containing methacrylate afforded copolymers containing covalently bound caffeine pendant groups. A free radical induced photoreaction and acid chloride reaction generated CMA requiring minimal isolation prior to polymerization. Using 2-ethylhexyl methacrylate as a comonomer, film-forming polymers containing 0, 5, and 13 mol % CMA provided insight into the effect of caffeine on physical properties. Caffeine influenced both thermal stability and Tg, showing a unique multistep thermal degradation profile similar to sidegroup elimination as observed for poly(N-vinylimidazole).45 ¹H NMR confirmed caffeine content, and UV-vis spectroscopy exhibited a characteristic absorbance for caffeine, shifted to higher wavelengths attributed to the extra π bond and resonance in CMA-containing copolymers. Finally, caffeine improved polymer moduli suggesting the aromatic structure stiffened polymer chains. These novel materials demonstrated the effect of the naturally occurring caffeine structure on polymer properties, including both thermal and thermomechanical influences. The higher $T_{\rm g}$ and storage moduli of low CMA contents (< 15 mol %) suggested that CMA could perform as a comonomer in acrylic polymers to impart specific physical properties and increase sustainability. Furthermore, future placement of caffeine further from the polymer backbone may encourage noncovalent π - π stacking and expand the library of caffeinecontaining polymers, promoting microphase-separation for the synthesis of elastomers and broadening the understanding and potential of caffeine in material applications.

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