Synthesis and Structure–Property Relationship of Amphiphilic Poly(2-ethyl-co-2-(alkyl/aryl)-2-oxazoline) Copolymers

Taha Behroozi Kohlan, Asu Ece Atespare, Mehmet Yildiz, Yusuf Ziya Menceloglu, Serkan Unal, and Bekir Dizman*

Cite This: ACS Omega 2022, 7, 40067−40077

ABSTRACT: Poly(2-oxazoline)s (POZs) are widely investigated for their applications in various fields due to their unique properties. To exploit and combine different characteristics of the POZ family, 2-oxazoline monomers can be copolymerized to prepare tailor-made copolymers with the desired glass transition temperature ($T_g$), melting temperature ($T_m$), amphiphility, and functionality. Here, we report the synthesis and characterization of 2-oxazoline monomers and a range of POZ copolymers produced, thereof. 2-Propyl-2-oxazoline (PrOZ) and 2-pentyl-2-oxazoline (PeOZ) monomers were synthesized by two different methods starting from nitriles or carboxylic acids. A number of POZ copolymers were synthesized by copolymerization of 2-ethyl-2-oxazoline (EOZ) with either one of PrOZ, PeOZ, or 2-phenyl-2-oxazoline (PhOZ) at three different compositions (25:75, 50:50, and 75:25) and three molecular weights (1000, 2000, and 5000 Da). The successful synthesis of the monomers and copolymers was demonstrated through their structural analysis by $^1$H NMR and FTIR. SEC results confirmed the targeted molar masses of the copolymers and living nature of the polymerization by showing low dispersity values. Thermal properties of the copolymers were studied using DSC and TGA. DSC studies revealed the amorph and random state of the copolymers with obtained $T_g$ values for the copolymers in the range of $-3$ to $84$ °C depending on their molecular weight and type of the side chain. While the presence of longer aliphatic side chains resulted in lower $T_g$ values, the presence of 2-phenyl substituents on the polymer led to higher $T_g$ values. The decomposition temperatures determined by TGA were in the range of 328 to 383 °C depending on the molecular weight, composition, and side chain of the copolymers. It was observed that higher molecular weights led to higher $T_g$ values and decomposition temperatures. While copolymers with aliphatic side chains exhibited a single-step decomposition profile, the decomposition of copolymers having aromatic side chains occurred in multiple steps. The variations in the molecular weight, composition, and side chains of the copolymers resulted in a library of tailorable amphiphilic copolymers suitable for multiple applications ranging from biomedical applications to composite manufacturing.

1. INTRODUCTION

Discovered more than 50 years ago, poly(2-oxazoline)s (POZs) are of great interest for the scientific community owing to their unique properties including ease of synthesis, tailorable properties, versatile functionalities, stimuli-responsiveness, and biocompatibility.¹,² POZs are obtained through cationic ring-opening polymerization (CROP) of 2-oxazoline monomers, which are 5-membered cyclic imino-ethers.³,⁴ CROP is a class of chain growth polymerization. The polymerization is initiated by the addition of an electrophilic initiator to the monomer solution. In the initiation step of 2-oxazolines, a nucleophilic attack of the nitrogen lone pair results in the formation of an oxazolinium cation.⁵ The polymerization proceeds with the addition of monomers to the active site of the growing chain and is terminated by addition of a nucleophile to the polymerization medium.⁶ The polymerization of 2-oxazolines is driven by the isomerization of cyclic imino-ethers to more stable tertiary amides which are thermodynamically more favorable.⁷

The unique chemistry of POZs offers the possibility to tailor the polymer structure to obtain desired properties by varying the initiators, 2-substituent groups of the monomer, and the terminating agents.⁸ Even though the use of numerous initiators and terminating agents has been reported in the literature to fine-tune the chemical and physical properties of POZs, altering the 2-substituent group of the monomer remains the most prevalent method for adjusting the polymer...
properties due to the large number of side chains as opposed to two terminal groups brought by initiator and terminating agent. Pendant side groups of the POZs greatly affect various properties of the polymer including solubility in water and organic solvents, crystallinity, stimuli-responsiveness, and amphiphilicity.\(^{9,10}\) In recent years, POZs with various pendant groups including alkyl, aryl,\(^{11}\) amino,\(^{12}\) aldehyde,\(^{13}\) alkene,\(^{14}\) and alkynes\(^{15-16}\) giving rise to different properties have been investigated for various applications including drug delivery,\(^{15,17,18}\) coatings,\(^{19,20}\) and composites.\(^{21}\)

Since CROP of 2-oxazolines is a heat-induced polymerization, two main methods of heat transfer, namely, microwave irradiation and conventional heating, have been proposed and investigated to control the polymerization rate.\(^{22}\) The scale of the synthesis, targeted molecular weight, and the synthesis infrastructure are important parameters for choosing the heating method. Despite the advantages of microwave assisted synthesis of the POZs such as shorter polymerization time and overcoming the limitations regarding the boiling points of the reagents through pressurized reactions,\(^{23}\) there are limitations in the industrial use of this method. The limited penetration depth of the irradiation, increased heat loss in larger systems,\(^{24}\) and the obstacles of incorporating the microwave assisted systems to the existing plants in terms of the required investments limit the possibility of using microwave assisted synthesis systems for large scale POZ production.\(^{25}\)

The hydrophilicity along with other properties of POZs can be fine-tuned by altering the side chain of the utilized monomer. The amide group on the polymer backbone provides an intrinsic hydrophilicity to the polymer, whereas the nature of 2-substituent groups can make the polymer hydrophilic, hydrophobic, or amphiphilic. For instance, the presence of methyl and ethyl pendant groups makes the polymers hydrophilic, whereas the presence of phenyl and pentyl pendant groups results in hydrophobic polymers.\(^{26}\) Moreover, the combination of monomers with varying degrees of hydrophilicity and hydrophobicity provides an amphiphilic character to the polymers. Therefore, the copolymerization of different monomers at varying compositions can be used as an effective mean to obtain POZ polymers with favorable properties such as amphiphilicity, and thermal and mechanical properties, etc. In addition to the types of monomers and compositions of the copolymers, the control of molecular weights of polymers substantially affects these properties.\(^{27}\) Copolymerization of 2-oxazoline monomers is feasible due to the controlled or living nature of the polymerization, which can be used to synthesize random,\(^{28}\) gradient,\(^{29}\) and block copolymers.\(^{30}\)

Although the POZs are widely used for biomedical applications with an emphasis on solution properties and thermoresponsiveness, other application fields such as organic electronics\(^{31}\) and carbon-based nanomaterial modifications\(^{32}\) have been reported owing to their fine-tunable properties. For such applications, the properties of POZs in the solid state such as \(T_g\) crystallinity, and thermal degradation are of great importance. Low molecular weight polymers are being widely investigated for their potential applications in additive manufacturing, injection molding, and plasticizing.\(^{33,34}\) Moreover, these polymers can be used as compatibilizers to enhance the processability of materials.\(^{35}\) Rubberlike materials such as polymers that exhibit a \(T_g\) below their utilization temperature are used in a variety of fields including adhesives, compatibilizers, plasticizers, fillers, etc.\(^{36}\) On the other hand, crystallinity of a polymer contributes to its application in other fields such as encapsulation, entrapment, and thermoresponsive release of desired substances.\(^{37}\) Thus, the ability to tailor the polymer structure in such a way to exhibit the desired thermal properties is an important factor in its applications in various fields. It has been reported that the functionality of the side chain, length of the side chains in the case of an aliphatic species, and the number of repeating units greatly affect the thermal properties of POZs.\(^{38}\) For instance, side chains up to three carbons result in amorphous polymers while poly(2-butyl-2-oxazoline) shows a semicrystalline behavior with a melting temperature of 150 °C.\(^{39}\) Moreover, thermal degradation temperature defines the maximum temperature, conditions of polymer processing and production method, and the final application of the polymer.\(^{40}\) Thus, we sought to investigate the properties of low molar mass POZ copolymers to examine the possibility of exploiting their properties and their implementation in novel applications.

In this study, we report the synthesis of two 2-oxazoline monomers (PrOZ and PeOZ) via two methods and a scalable synthesis method via conventional heating to obtain a library of well-defined POZ copolymers having different molecular weights and compositions. The synthesized PrOZ and PeOZ and E0OZ monomers had aliphatic groups, whereas PhOZ contained an aromatic group on the 2-position. E0OZ was copolymerized with other monomers to obtain PE0Z–PPrOZ, PEOZ–PPhOZ, and PEOZ–PPhOZ copolymers at three different compositions (25:75, 50:50, and 75:25) and three different relatively low molar masses (1000, 2000, and 5000 g/mol). The obtained POZ copolymers were characterized by \(^1\)H NMR, FTIR, and SEC to study their structure, copolymerization efficiency at the implemented reaction conditions, molecular weights, and dispersity indices. Thermal properties such as crystallinity, \(T_g\), and thermal degradation were also widely investigated by DSC and TGA to study the effect of the side chain type and length along with the number of repeating units on the polymer properties.

2. EXPERIMENTAL SECTION

2.1. Materials. 2-Ethyl-2-oxazoline (EOZ), 2-phenyl-2-oxazoline (PhOZ), chlorobenzene, methanol, and hexanoic acid were purchased from Sigma-Aldrich. Monomers and chlorobenzene were dried over calcium hydride (CaH\(_2\)), distilled, and kept over 4 Å molecular sieves before their use in polymerizations. Trifluoromethanesulfonic acid (TIOH) and oxalyl chloride were purchased from Acros Organics. Butyronitrile and 2-chloroethylamine hydrochloride were purchased from ABCR. Sodium hydroxide (NaOH) and potassium hydroxide (KO\(_2\)) were purchased from ISOLAB. Ethanolamine, Ca\(_2\), dichloromethane (DCM), zinc acetate dihydrate (Zn(OAc)\(_2\))·2H\(_2\)O), triethylamine (TEA), and sodium sulfate (Na\(_2\)SO\(_4\)) were purchased from Merck. Unless it is stated otherwise, all chemicals were used as received.

2.2. Instruments. \(^1\)H NMR spectra were recorded on a 500 MHz Varian spectrometer in CDCl\(_3\) and CD\(_3\)OD. FTIR spectra were recorded on ThermoScientific Nicolet iS50 FTIR spectrometer using an attenuated total reflectance (ATR) accessory. The transmission mode was used, and the resolution was 16 cm\(^{-1}\). Size exclusion chromatography (SEC) measurements were carried out on Malvern VISCOTEK GPCmax-Viscotek TDA305 with mixed D5000-D3000-D1000-DGuard column and refractive index detector. The column temperature was 55 °C, and the injection volume was 100 μL. DMF was
standards were prepared by calibrating the instrument with poly(2-ethyl-2-oxazoline) (PEOZ) standards. PEOZ synthesis methods used are shown in Scheme 1. In this study, the nitrile route was employed to synthesize five PEOZ polymers with the synthesis method starting from nitrile groups (yield: 53%), which was kept over 4 Å molecular sieves.

2.3.2. Synthesis of 2-Pentyl-2-oxazoline. 2.3.2.1. Synthesis of Hexanoyl Chloride. Oxalyl chloride (82 g, 0.64 mol, 1.5 equiv) was added dropwise to ice-cooled hexanoic acid (50 g, 0.43 mol, 1 equiv) under N₂ purge. The reaction mixture was allowed to warm to room temperature and then was heated to reflux for 1 h. After cooling down to room temperature, the excess oxalyl chloride was removed by distillation at 61 °C under 1 atm pressure. The product (hexanoyl chloride) was used in the next step without further purification.

2.3.2.2. Synthesis of N-(2-Chloroethyl) Hexanamide. Triethylamine (161.8 mL, 1.161 mol, 2.7 equiv) was added to 700 mL of ice-cooled DCM in a 1 L round-bottom flask followed by the addition of 2-chloroethylamine hydrochloride (62.3 g, 0.537 mol, 1.25 equiv) into the flask. After purging with N₂, the hexanoyl chloride obtained in the first step was added to the ice-cooled flask, dropwise. The mixture was allowed to warm to room temperature and kept stirring at room temperature overnight. The mixture was filtered to remove triethylamine hydrochloride, and the filtrate was evaporated under vacuum to remove DCM and excess TEA. DCM was then added to dissolve the product. The solution was washed twice with sodium bicarbonate solution and once with brine. The organic phase was separated and dried over Na₂SO₄ followed by its filtration. DCM present in the filtrate was evaporated under reduced pressure to obtain 55.7 g of N-(2-chloroethyl) hexanamide as a solid product at room temperature (yield: 73%).

2.3.2.3. Synthesis of 2-Pentyl-2-oxazoline Monomer (PeOZ). The N-(2-chloroethyl) hexanamide (55.7 g, 1 equiv) obtained in the second step was dissolved in methanol (550 mL) to yield an overall concentration of 10 wt % in methanol and added into a 180 mL methanolic solution of NaOH (18.8 g of NaOH, 1.5 equiv). The solution was heated to reflux and kept stirring overnight. After cooling down to room temperature, the mixture was filtered and the filtrate was concentrated under reduced pressure. The solution was diluted with 40 mL of distilled water and extracted into DCM (3× 150 mL). Organic phases were combined and dried with Na₂SO₄ (30 g). Na₂SO₄ was filtered, and DCM present in the filtrate was evaporated under reduced pressure. The residue was distilled at 38 °C under vacuum (at 1 mbar) to obtain 24.0 g of 2-pentyl-2-oxazoline (yield: 54%).

2.4. General Copolymer Synthesis Procedure. Polymerizations were carried out in round-bottom flasks under
continuous N₂ purge. Before introducing materials, the flasks were heated to 120 °C, vacuumed, and cooled to ambient temperature under nitrogen flow. Polymerizations were performed in chlorobenzene with an overall monomer concentration of 4 M. TfOH was used as the polymerization initiator. The monomer to initiator ratio ([M]/[I]) was set to be 10, 20, and 50 to obtain different degrees of polymerization and molar masses of 1000 g mol⁻¹, 2000 g mol⁻¹, and 5000 g mol⁻¹, respectively. The polymerization times and temperatures for the copolymers are presented in Table 1. After cooling the reaction mixture to room temperature using an ice bath, polymerizations were terminated with methanolic KOH solution overnight. To investigate the effect of varying the copolymer composition on its properties, a number of random copolymers were synthesized through the copolymerization of POZ with PrOZ, PeOZ, or PhOZ with the targeted molecular weights of 1000, 2000, and 5000 g mol⁻¹ following the general polymerization procedure described above. The [M]/[I] was calculated by taking into account the total concentrations of two monomers. The targeted compositions were 25:75, 50:50, and 75:25 (molar ratio) for POZ:other polymer (PPrOZ, PPeOZ, PPhOZ) resulting in 27 copolymers. The synthesis of the copolymers is shown in Scheme 2.

### Scheme 2. Synthesis of the Copolymers

**Table 1. Polymerization Conditions for Copolymers**

| Copolymer | Temp (°C) | Time (min) |
|-----------|-----------|------------|
| PEOZ–PPrOZ | 80 | 30, 60, and 120 for 1, 2, and 5 kg mol⁻¹, respectively |
| PEOZ–PPeOZ | 80 | 60, 120, and 240 for 1, 2, and 5 kg mol⁻¹, respectively |
| PEOZ–PPhOZ | 95 | 60, 120, and 240 for 1, 2, and 5 kg mol⁻¹, respectively |

### 2.4.2. Purification of POZ–PPhOZ

The solvents (chlorobenzene and methanol) of the reaction mixture were evaporated under reduced pressure. THF was added to the resulting white solid to dissolve the copolymer. The mixture was filtered to remove the excess KOH, and the filtrate was evaporated under reduced pressure. The copolymer was dissolved in methanol and precipitated into ice-cooled diethyl ether. The precipitate was filtered and dried at room temperature under vacuum to give the final copolymers. This purification procedure was followed for the purification of POZ–PPhOZ copolymers with different compositions and molecular weights.

### 3. RESULTS AND DISCUSSION

#### 3.1. Structural Analysis of Synthesized and Commercial Monomers

Structural analysis of the synthesized (PrOZ and PeOZ) and commercial (EOZ and PhOZ) monomers was performed by ¹H NMR and FTIR as shown in Figure 1a,b, respectively. On the ¹H NMR spectra, two peaks associated with protons of the oxazoline ring (a and b) appeared at δ 3.75 and δ 4.10 ppm. The transformation of these peaks to new peaks associated with the protons of the polymer backbone was monitored in order to follow the polymerizations. The peaks associated with protons present on the side groups are assigned on the spectra with matching integral values to the number of hydrogen atoms of methylene and methyl groups. In the FTIR spectra shown in Figure 1b, the sharp peak at 1660 cm⁻¹ is attributed to the stretching of C=O in all monomers. For the PhOZ, the C=C peak is marked at 1570 cm⁻¹. All of the monomers, asymmetric and symmetric stretches of C−O−C peaks appeared at around 1000 cm⁻¹ in the fingerprint region. The peaks associated with C−H bonds (CH bonds in CH₂ and CH₃ groups) on the 2-oxazoline ring and the side groups appeared at 1470 cm⁻¹ and around 3000 cm⁻¹, respectively. The peak associated with sp² hybridized C−H of the phenyl ring appeared at 3100 cm⁻¹. Out of plane bending of C−H on phenyl ring can be related to the peaks that appeared between 600 and 800 cm⁻¹. The characteristic peaks are provided on the spectra that confirm the structure of synthesized and commercial monomers. To follow the polymerizations, the transformations of C−O and C=N peaks of the monomers were monitored during polymerizations.

#### 3.2. Structural Analysis of Synthesized Copolymers

To thoroughly investigate the effects of the systematic variation of molecular weight and composition on the properties of the copolymer, a series of random POZ copolymers with targeted molar masses of 1000, 2000, and 5000 g mol⁻¹ and compositions of 25:75, 50:50, and 75:25 were synthesized. All polymerizations were initiated with TfOH and terminated with methanolic KOH solution. The synthesized copolymers were analyzed by ¹H NMR and FTIR to confirm their structures. Figure 2a–c shows the ¹H NMR spectra of PEOZ–PPrOZ 5K, PEOZ–PPeOZ 5K, and PEOZ–PPhOZ 5K random copolymers with different compositions and molecular weights.

*Note: m:n ratios are 25:75, 50:50, and 75:25.*
compositions, respectively. The $^1$H NMR spectra of copolymers show the disappearance of two peaks at $\delta$ 3.75 and $\delta$ 4.10 ppm, which are assigned to the protons of the 2-oxazoline monomer ring. The peaks associated with the protons of the methylene groups on the polymer backbone appeared at $\delta$ 3.4–3.6 ppm. The $^1$H NMR results were used to determine the final compositions of copolymers. To compare the composition of synthesized copolymers with the feed ratio of monomers, the distinct peaks of the methyl groups of the alkyl or C−H peaks of aryl side chains on $^1$H NMR spectra were integrated. The increases in the intensity of the peaks associated with the protons of the methyl groups of the side chains of PEOZ (peak “b”) compared to the protons of the methyl groups of the side chains of PPrOZ and PPeOZ (peak “d”) were clearly observed from the spectra as the ratios of the ethyl group to the propyl or pentyl group were varied from 25:75, to 50:50, and then to 75:25. To calculate the composition of the PEOZ−PPhOZ copolymer, the peaks associated with the protons of the phenyl group ($\delta$ 7.4 ppm) were compared to the protons of the methyl group of the side chain of PEOZ ($\delta$ 1.1 ppm). Table 2 summarizes the compositions of the obtained copolymers and the monomer feed ratios. The results indicate that the copolymer compositions are the same as the monomer feed ratios, which show that, at the implemented polymerization conditions, the ratio of the monomer feed determines the final composition of the copolymers. This behavior demon-

Figure 1. (a) $^1$H NMR spectra of EOZ, PrOZ, PeOZ, and PhOZ recorded in CDCl$_3$ and (b) FTIR spectra of 2-oxazoline monomers: (a) EOZ, (b) PrOZ, (c) PeOZ, and (d) PhOZ.

Figure 2. Structural analysis of copolymers. $^1$H NMR spectra of (a) PEOZ−PPrOZ SK, (b) PEOZ−PPeOZ SK, and (c) PEOZ−PPhOZ SK at different compositions. (d) FTIR spectra of copolymers with different side groups at the same composition.
strates the proximity of the polymerization rate of used monomers at given temperatures.

The synthesized copolymers were also characterized by FTIR spectroscopy to confirm their structures. Figure 2d shows the FTIR spectra of copolymers with 5000 g mol\(^{-1}\) molar mass and 50:50 composition. The sharp peak associated with C\(=\)N stretching of monomers at 1640 cm\(^{-1}\) is altered to an amide peak present in the polymer structure at 1660 cm\(^{-1}\). The peaks associated with the C\(=\)O stretching of the monomer ring disappeared after the polymerizations. Out of plane bending peaks of the phenyl ring are observed in the range 600–800 cm\(^{-1}\) along with the C\(=\)C peak of phenyl ring at 1579 cm\(^{-1}\). The –OH stretching peak appeared on the copolymer spectra, which was not visible on dry monomers.

Table 2. Molecular Weight Results of Copolymers (by SEC) and Copolymer Composition Results (by \(^1\)H NMR) along with Reaction Yields

| Copolymer       | Composition by \(^1\)H NMR | SEC | PMMA std | yield (%) |
|-----------------|-----------------------------|-----|----------|-----------|
| PEOZ–PPrOZ 25:75 1K | 25:75                       | 794 | 650      | 1.18      | 1594  | 917  | 1.61 | 74   |
| PEOZ–PPrOZ 25:75 2K | 25:75                       | 1642| 1,240    | 1.28      | 3452 | 2309 | 1.4  | 73   |
| PEOZ–PPrOZ 25:75 5K | 26:74                       | 4117| 3,643    | 1.21      | 7863 | 7085 | 1.15 | 76   |
| PEOZ–PPrOZ 50:50 1K | 43:57                       | 752 | 626      | 1.15      | 1206 | 738  | 1.5  | 72   |
| PEOZ–PPrOZ 50:50 2K | 51:49                       | 1702| 1,338    | 1.2       | 2870 | 2130 | 1.24 | 76   |
| PEOZ–PPrOZ 50:50 5K | 50:50                       | 5203| 3,606    | 1.3       | 8291 | 6032 | 1.23 | 77   |
| PEOZ–PPrOZ 75:25 1K | 72:28                       | 678 | 535      | 1.18      | 1305 | 591  | 1.79 | 77   |
| PEOZ–PPrOZ 75:25 2K | 75:25                       | 1778| 1,552    | 1.15      | 3726 | 3214 | 1.14 | 76   |
| PEOZ–PPrOZ 75:25 5K | 74:26                       | 4746| 3,697    | 1.2       | 7666 | 6173 | 1.16 | 81   |
| PEOZ–PPeOZ 25:75 1K | 25:75                       | 1000| 854      | 1.13      | 2076 | 1634 | 1.2  | 69   |
| PEOZ–PPeOZ 25:75 2K | 23:77                       | 1909| 1,503    | 1.23      | 3981 | 2923 | 1.3  | 71   |
| PEOZ–PPeOZ 25:75 5K | 25:75                       | 4915| 2910     | 1.46      | 9134 | 5739 | 1.36 | 73   |
| PEOZ–PPeOZ 50:50 1K | 49:51                       | 964 | 812      | 1.2       | 1956 | 1532 | 1.25 | 70   |
| PEOZ–PPeOZ 50:50 2K | 52:48                       | 1823| 1,662    | 1.18      | 3812 | 3433 | 1.17 | 71   |
| PEOZ–PPeOZ 50:50 5K | 51:49                       | 4784| 4,218    | 1.36      | 8930 | 8076 | 1.26 | 74   |
| PEOZ–PPeOZ 75:25 1K | 73:27                       | 925 | 715      | 1.21      | 1903 | 1083 | 1.58 | 73   |
| PEOZ–PPeOZ 75:25 2K | 75:25                       | 1937| 1,665    | 1.15      | 4034 | 3446 | 1.14 | 76   |
| PEOZ–PPeOZ 75:25 5K | 74:26                       | 5251| 3,782    | 1.3       | 9657 | 7335 | 1.22 | 78   |
| PEOZ–PPhOZ 25:75 1K | 30:70                       | 1189| 832      | 1.331     | 2501 | 2237 | 1.24 | 73   |
| PEOZ–PPhOZ 25:75 2K | 27:73                       | 2175| 1,681    | 1.19      | 4489 | 3461 | 1.18 | 75   |
| PEOZ–PPhOZ 25:75 5K | 22:78                       | 4622| 3,327    | 1.29      | 8647 | 6527 | 1.22 | 76   |
| PEOZ–PPhOZ 50:50 1K | 49:51                       | 1035| 1,057    | 1.127     | 2157 | 2156 | 1.14 | 74   |
| PEOZ–PPhOZ 50:50 2K | 52:48                       | 2332| 1,815    | 1.2       | 4783 | 3733 | 1.18 | 75   |
| PEOZ–PPhOZ 50:50 5K | 46:54                       | 4999| 3,690    | 1.29      | 8798 | 6954 | 1.20 | 77   |
| PEOZ–PPhOZ 75:25 1K | 75:25                       | 863 | 1,002    | 1.13      | 1759 | 2033 | 1.15 | 76   |
| PEOZ–PPhOZ 75:25 2K | 76:24                       | 1871| 1,538    | 1.19      | 3905 | 3181 | 1.18 | 77   |
| PEOZ–PPhOZ 75:25 5K | 74:26                       | 3596| 2,288    | 1.39      | 7005 | 4614 | 1.32 | 79   |

Figure 3. \(T_g\) values of copolymers based on composition (i) and molar mass (ii): (a) PEOZ–PPrOZ, (b) PEOZ–PPeOZ, and (c) PEOZ–PPhOZ.
This peak can be associated with the terminal –OH group and the absorbed moisture resulting from the hydrophilicity of PEOZ carrying copolymers. FTIR spectra of the copolymers with targeted molar masses of 1000 and 2000 g mol\(^{-1}\) and different compositions exhibited similar peaks as the copolymers with molar mass of 5000 g mol\(^{-1}\) and 50:50 composition.

The molecular weight and dispersity values of the synthesized copolymers measured by SEC are shown in Table 2. Moreover, values for yields are reported in Table 2 based on the amount of the material obtained after the purification steps.

The SEC measurements were performed using two different standards of poly(methyl methacrylate) (PMMA) and the prepared PEOZ homopolymers standard. Since the synthesized copolymers have an amphiphilic nature, neither of these standards solely would have been sufficient to characterize the copolymers due to the hydrophilicity of PEOZ and hydrophobicity of PMMA. Thus, both standards were used to investigate the molar mass and D of the copolymers. Although the results do not show the exact molar mass, the range of the measurements indicated the successful synthesis of copolymers with molar masses of 1000, 2000, and 5000 g mol\(^{-1}\). Moreover, the proximity of the molar masses of different copolymers having the same targeted molecular weight in both standards indicated the accuracy of making a comparison among them to investigate the effect of other parameters on polymer properties other than the molecular weight. As presented in Table 2, synthesized copolymers have narrow polydispersity values which confirm the living nature of the polymerization.

### 3.3. Thermal Analysis

#### 3.3.1. DSC Results

The thermal properties such as \(T_g\) and crystallinity of the synthesized copolymers were studied using DSC. As reported in the literature, the length of the polymer side chain and the number of repeating units act as influential factors in determining the crystallinity and \(T_g\) of the polymer.\(^{38}\) The effects of having aliphatic chains with two, three, and five carbons and phenyl group as the aromatic group on the thermal properties of the copolymers of different molecular weights and compositions have been studied. Figure 3 shows the \(T_g\) values of PEOZ—PPrOZ, PEOZ—PPeOZ, and PEOZ—PPhOZ copolymers based on composition and molar mass. DSC thermograms are presented in Supporting Information Figures S1–S3. The copolymerization of EOZ with PrOZ, PeOZ, and PhOz has resulted in copolymers having a \(T_g\) value that lies in between the \(T_g\) values of the homopolymers of each monomer depending on the copolymer composition. The presence of only one \(T_g\) without \(T_m\) and \(T_m\), for all synthesized copolymers indicated their amorphous state and random structure.

As seen from Figure 3, copolymerization of a monomer having a longer aliphatic side chain than ethyl as in PEOZ has lowered the \(T_g\) of the obtained copolymers. The \(T_g\) values of PEOZ—PPrOZ (Figure 3a,ii) and PEOZ—PPeOZ (Figure 3b,ii) copolymers at the same molecular weights increased as the molar content of EOZ increased from 25% to 50% and to 75% in the copolymer composition. This can be attributed to having a higher content of short side chains resulting in higher packing density and stronger amide dipole interactions arising from the proximity of the backbones of the copolymer chains. Unlike the homopolymers of PPeOZ that are in a semicrystalline state, only a \(T_g\) value is observed for the synthesized PEOZ—PPeOZ copolymers. The incorporation of PEOZ, even at a low molar ratio (e.g., 25%), in the copolymer structure with PPeOZ causes the neighboring 2-pentyl side chains to be pushed apart preventing the side chain crystallinity. Thus, with the decreased packing density and in the absence of side chain crystallinity, the semicrystalline structure of PPeOZ homopolymer is altered to an amorphous state for the PEOZ—PPeOZ copolymers. Investigating the \(T_g\) values of the copolymers of the same molar mass having aliphatic side chains reveals the effect of the length of the side chain on the copolymer properties. The \(T_g\) value of the copolymer is decreased with the increase in the content of the monomer with a longer side chain. For instance, as shown in Figure 3a,ii, \(T_g\) values for PEOZ—PPrOZ 1K copolymers are 11.37, 23.13, and 30.03 °C while for PEOZ—PPeOZ 1K copolymers, \(T_g\) values are −3.35, 8.32, and 18.39 °C, for the compositions of 25:75, 50:50, and 75:25, respectively. The decrease in \(T_g\) values has resulted in obtaining rubber-like materials with a \(T_g\) lower than ambient temperature. The rubbery characteristic of the obtained copolymers can be exploited for its plasticizing effects by having long and hydrophobic alkyl side chains while avoiding the crystallinity resulting from incorporating PEOZ in the polymer structure.

For PEOZ—PPhOZ copolymers having the same molar mass, an increasing trend was observed for \(T_g\) values with the increase in the content of PhOZ or decrease in the content of EOZ. The increase in \(T_g\) with respect to the increase in PhOZ content is attributed to the presence of rigid aromatic phenyl ring and possible π-stacking of phenyl side groups.

Investigating the effects of altering molar mass on \(T_g\) revealed that an increase in the molar mass had resulted in higher \(T_g\) values for all copolymers of the same composition. For all copolymers, as the molar mass increased, a higher \(T_g\) value was observed due to the stronger interactions of the copolymer chains having a higher number of repeating units. Moreover, the higher number of repeating units resulted in more entanglements of the polymer chains which resulted in higher \(T_g\) values.

The DSC results revealed that the length, structure, and interactions (functionalities) of side chains along with the molar mass of the copolymer affect the thermal properties of the copolymers such as \(T_g\). With a longer side chain, the \(T_g\) is lowered since the longer side chain lowers the packing density and facilitates the chain motion. Moreover, having a shorter side chain results in the proximity of backbones of the copolymer chains. Thus, the amide dipole interactions are stronger leading to a higher \(T_g\). On the other hand, longer side chains increase the distance between amide groups of polymer chains, which facilitates the relaxation of the backbone of copolymer chains, thus decreasing the \(T_g\).\(^{49}\) For the copolymers with aromatic side chains, interactions of the side chain functionalities were the dominant factor in determining the thermal properties. The π-stacking of 2-phenyl substituents possibly increased the packing density of the polymer chains, which resulted in higher \(T_g\) values. As all the copolymers show a single \(T_g\) value without crystallization or melting peaks, it can be stated that all copolymers are in an amorphous and random state.

Figure 4 shows the \(T_g\) values of the synthesized copolymers with respect to their molecular weight. For each copolymer, \(T_g\) increased with an increase in the molecular weight of the polymer. For all molecular weights, it was observed that the PEOZ—PPeOZ 25:75 copolymer has the lowest \(T_g\) value due to having the highest number of the longest alkyl side chains among the copolymers. Additionally, for all molecular weights,
A series of POZ copolymers were synthesized and characterized to investigate the structure–property relationship by altering the side chain, composition, and molecular weights of the copolymers. The copolymers were synthesized from copolymerization of PrOZ, PeOZ, and PhOZ with EOZ in three different compositions of 25:75, 50:50, and 75:25. The targeted molecular weights of the copolymers were 1000, 2000, and 5000 Da. FTIR and $^1$H NMR results confirm the successful synthesis of the monomers and copolymers with the desired compositions. SEC measurements indicate a narrow polydispersity, which confirms the living nature of the cationic ring-opening polymerization. The thermal properties of the copolymers were studied using DSC and TGA. DSC results revealed that copolymers are amorphous and random have a single $T_g$ and do not show any crystallization or melting peaks. By altering the side chain of the copolymers along with having different molecular weights, a wide range of $T_g$ values from −3 to 84 °C is obtained, which provides the possibility to have the desired $T_g$ value with the favored molecular weight and side chain. It was observed that increasing the length of the alkyl side chain resulted in a decrease in $T_g$ values because of the lower packing density while the incorporation of 2-phenyl substituents resulted in an increase in $T_g$ values due to the π-stacking. Moreover, regardless of the side chain, $T_g$ increased with the increase in the molecular weight of the copolymers. The DSC results revealed the effect of the number of repeating units on the packing density and the number of entanglements used for termination. Figure 6 shows the onset temperature of degradation for copolymers based on composition and molar mass. The decomposition temperatures demonstrate a decreasing trend with respect to the increase in the length of the aliphatic side chain. When the decomposition temperatures of all copolymers of the same compositions are investigated, they increase with respect to the increasing molecular weight. For the polymers with aliphatic side chains having the same molecular weight, the copolymers with a composition closer to the homopolymer of each type (i.e., 25:75 and 75:25) have higher decomposition temperatures compared to the composition of 50:50 that has lower decomposition temperatures. For copolymers of the same molecular weight having a phenyl group as the side chain, the decomposition temperatures increase with the increase in the PhOZ content. This behavior is also shown in Figure 5c where decomposition temperatures of PEOZ–PPrOZ 5K, PEOZ–PPeOZ 5K, and PEOZ–PPhOZ 5K copolymers are examined. The degradation parameters, such as onset temperature ($T_{d,onset}$), completion temperature ($T_{d,endset}$), and 5% weight loss ($T_{d,5\%}$) are summarized in Table S1 (see SI).

4. CONCLUSIONS

In general, the weight loss seen below 120 °C is related to the evaporation of water absorbed by the copolymers. The copolymer decomposition starts above 300 °C, and the onset temperatures of copolymers are in the range 328–383 °C. During degradation steps, the weight loss is completed with less than 5% residue, which validates the efficiency of the implemented purification methods to remove the excess KOH that, for a desired $T_g$ value (e.g., 34 °C), multiple copolymers with different side chains and molecular weights (i.e., PEOZ–PPrOZ 75:25 2K, PEOZ–PPrOZ 50:50 2K, and PEOZ–PPrOZ 25:75 5K) can be synthesized and utilized based on the required final properties. This multiplicity of choices provides the opportunity to obtain the required final properties (e.g., $T_g$) while having the possibility to manipulate other characteristics of the polymer such as molecular weight, amphiphilicity, solution viscosity, and functionalities.

3.3.2. TGA Results. Thermal stability and degradation temperatures of the copolymers were determined by TGA. The results indicate that the thermal degradation of POZ copolymers with aliphatic side chains proceeds with one-step decomposition. However, the incorporation of the 2-phenyl substituent in the polymer structure gives rise to further decomposition shoulders, which results in a multistep decomposition. This behavior is observed for all compositions of PEOZ–PPhOZ copolymers. The multistep shoulders indicate that PEOZ–PPhOZ copolymers have more complex decomposition mechanisms compared to the copolymers with aliphatic chains.

In general, the weight loss seen below 120 °C is related to the evaporation of water absorbed by the copolymers. The copolymer decomposition starts above 300 °C, and the onset temperatures of copolymers are in the range 328–383 °C. The DSC results revealed the effect of the number of repeating units on the packing density and the number of entanglements used for termination. Figure 6 shows the onset temperature of degradation for copolymers based on composition and molar mass. The decomposition temperatures demonstrate a decreasing trend with respect to the increase in the length of the aliphatic side chain. When the decomposition temperatures of all copolymers of the same compositions are investigated, they increase with respect to the increasing molecular weight. For the polymers with aliphatic side chains having the same molecular weight, the copolymers with a composition closer to the homopolymer of each type (i.e., 25:75 and 75:25) have higher decomposition temperatures compared to the composition of 50:50 that has lower decomposition temperatures. For copolymers of the same molecular weight having a phenyl group as the side chain, the decomposition temperatures increase with the increase in the PhOZ content. This behavior is also shown in Figure 5c where decomposition temperatures of PEOZ–PPrOZ 5K, PEOZ–PPeOZ 5K, and PEOZ–PPhOZ 5K copolymers are examined. The degradation parameters, such as onset temperature ($T_{d,onset}$), completion temperature ($T_{d,endset}$), and 5% weight loss ($T_{d,5\%}$) are summarized in Table S1 (see SI).

4. CONCLUSIONS

A series of POZ copolymers were synthesized and characterized to investigate the structure–property relationship by altering the side chain, composition, and molecular weights of the copolymers. The copolymers were synthesized from copolymerization of PrOZ, PeOZ, and PhOZ with EOZ in three different compositions of 25:75, 50:50, and 75:25. The targeted molecular weights of the copolymers were 1000, 2000, and 5000 Da. FTIR and $^1$H NMR results confirm the successful synthesis of the monomers and copolymers with the desired compositions. SEC measurements indicate a narrow polydispersity, which confirms the living nature of the cationic ring-opening polymerization. The thermal properties of the copolymers were studied using DSC and TGA. DSC results revealed that copolymers are amorphous and random have a single $T_g$ and do not show any crystallization or melting peaks. By altering the side chain of the copolymers along with having different molecular weights, a wide range of $T_g$ values from −3 to 84 °C is obtained, which provides the possibility to have the desired $T_g$ value with the favored molecular weight and side chain. It was observed that increasing the length of the alkyl side chain resulted in a decrease in $T_g$ values because of the lower packing density while the incorporation of 2-phenyl substituents resulted in an increase in $T_g$ values due to the π-stacking. Moreover, regardless of the side chain, $T_g$ increased with the increase in the molecular weight of the copolymers. The DSC results revealed the effect of the number of repeating units on the packing density and the number of entanglements used for termination. Figure 6 shows the onset temperature of degradation for copolymers based on composition and molar mass. The decomposition temperatures demonstrate a decreasing trend with respect to the increase in the length of the aliphatic side chain. When the decomposition temperatures of all copolymers of the same compositions are investigated, they increase with respect to the increasing molecular weight. For the polymers with aliphatic side chains having the same molecular weight, the copolymers with a composition closer to the homopolymer of each type (i.e., 25:75 and 75:25) have higher decomposition temperatures compared to the composition of 50:50 that has lower decomposition temperatures. For copolymers of the same molecular weight having a phenyl group as the side chain, the decomposition temperatures increase with the increase in the PhOZ content. This behavior is also shown in Figure 5c where decomposition temperatures of PEOZ–PPrOZ 5K, PEOZ–PPeOZ 5K, and PEOZ–PPhOZ 5K copolymers are examined. The degradation parameters, such as onset temperature ($T_{d,onset}$), completion temperature ($T_{d,endset}$), and 5% weight loss ($T_{d,5\%}$) are summarized in Table S1 (see SI).
of the copolymers. TGA results indicated a single-step degradation for copolymers having aliphatic side chains while the copolymers carrying 2-phenyl substituent groups exhibited a multistep degradation revealing a more complex degradation mechanism for these copolymers. It was also observed that the longer aliphatic side chain results in a lower degradation temperature. Moreover, the degradation temperatures have an increasing trend with an increase in the molecular weights of the copolymers. The effect of the copolymer composition on the degradation temperature was also studied. It was observed that, for the copolymers having aliphatic side chains, the 50:50 composition possesses the lowest degradation temperature compared to other compositions. For the PEOZ−PPhOZ copolymers, increasing the PhOZ content resulted in an increase in the degradation temperature.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.2c04809.

DSC thermograms and degradation temperatures (PDF)

AUTHOR INFORMATION

Corresponding Author
Bekir Dizman − Integrated Manufacturing Technologies Research and Application Center & Composite Technologies Center of Excellence and Faculty of Engineering and Natural Sciences, Materials Science and Nano Engineering, Sabanci University, Istanbul 34956, Turkey; orcid.org/0000-0002-4909-8403; Email: bekirdizman@sabanciuniv.edu

Authors
Taha Behroozi Kohlan − Integrated Manufacturing Technologies Research and Application Center & Composite Technologies Center of Excellence and Faculty of Engineering and Natural Sciences, Materials Science and Nano Engineering, Sabanci University, Istanbul 34956, Turkey

Mehmet Yildiz − Integrated Manufacturing Technologies Research and Application Center & Composite Technologies Center of Excellence and Faculty of Engineering and Natural Sciences, Materials Science and Nano Engineering, Sabanci University, Istanbul 34956, Turkey

Yusuf Ziya Menceloglu − Integrated Manufacturing Technologies Research and Application Center & Composite Technologies Center of Excellence and Faculty of Engineering and Natural Sciences, Materials Science and Nano Engineering, Sabanci University, Istanbul 34956, Turkey; orcid.org/0000-0003-0296-827X

Serkan Unal − Integrated Manufacturing Technologies Research and Application Center & Composite Technologies Center of Excellence and Faculty of Engineering and Natural Sciences, Materials Science and Nano Engineering, Sabanci University, Istanbul 34956, Turkey; orcid.org/0000-0003-4423-6202

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c04809

Funding
This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) with the project code 118Z898.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
The authors would like to thank Dr. Zeynep Munteha Sahin for the helpful discussions on the obtained results.

REFERENCES
(1) Hoogenboom, R. Poly(2-Oxazoline)s: A Polymer Class with Numerous Potential Applications. Angew. Chemie - Int. Ed. 2009, 48 (43), 7978−7994.
(2) Nemati Mahand, S.; Aliakbarzadeh, S.; Moghaddam, A.; Salehi Moghaddam, A.; Salehi, A.; Kruppke, B.; Nasrollahzadeh, M.; Khonakdar, H. A. Polyoxazoline: A Review Article from Polymerization to Smart
Weight Poly(Ethylene Glycol): Mechanical, Thermal, and Morphology Properties. *J. Appl. Polym. Sci.* **2013**, *130* (6), 4576−4580.

(35) Zhou, Y.; Peng, Z.; Ji, J.; Wu, Y.; Chen, Z.; Huang, H.; Liu, S.; Zhao, J. Fluorinated Low Molecular Weight Poly(Phenylene Oxide): Synthesis, Characterization, and Application in Epoxy Resin toward Improved Thermal and Dielectric Properties. *Eur. Polym. J.* **2021**, *157*, 110674.

(36) Kempe, K.; Rettler, E. F. J.; Paulus, R. M.; Kuse, A.; Hoogenboom, R.; Schubert, U. S. A Systematic Investigation of the Effect of Side Chain Branching on the Glass Transition Temperature and Mechanical Properties of Aliphatic (Co-)Poly(2-Oxazoline). *Polymer (Guildf)* **2013**, *54* (8), 2036−2042.

(37) Karavelidis, V.; Karavas, E.; Giliopoulos, D.; Papadimitriou, S.; Bikiaris, D. Evaluating the Effects of Crystallinity in New Biocompatible Polyester Nanocarriers on Drug Release Behavior. *Int. J. Nanomedicine* **2011**, *6*, 3021.

(38) Oleszko, N.; Utrata-Wesołek, A.; Walach, W.; Libera, M.; Hercog, A.; Szelauga, U.; Domański, M.; Trzebiacka, B.; Dworak, A. Crystallization of Poly(2-Isopropyl-2-Oxazoline) in Organic Solutions. *Macromolecules* **2015**, *48* (6), 1852−1859.

(39) Litt, M.; Rahl, F.; Roldan, L. G. Polymerization of Cyclic Imino Ethers. VI. X-Ray Study of Some Polyaziridines. *J. Polym. Sci. Part A-2 Polym. Phys.* **1969**, *7* (3), 463−473.

(40) Pospíšil, J.; Horák, Z.; Krulis, Z.; Nespurek, S.; Kuroda, S. I. Degradation and Aging of Polymer Blends. I. Thermomechanical and Thermal Degradation. *Polym. Degrad. Stab.* **1999**, *65* (3), 405−414.

(41) Boerman, M. A.; Van Der Laan, H. L.; Bender, J. C. M. E.; Hoogenboom, R.; Jansen, J. A.; Leeuwenburgh, S. C.; Van Hest, J. C. M. Synthesis of PH- and Thermoresponsive Poly(2-n-Propyl-2-Oxazoline) Based Copolymers. *J. Polym. Sci., Part A: Polym. Chem.* **2016**, *54*, 1573−1582.

(42) Kaberov, L. I.; Verbraeken, B.; Riatsetva, A.; Brus, J.; Radulescu, A.; Talmon, Y.; Stepanek, P.; Hoogenboom, R.; Filipov, S. K. Fluorophilic-Lipophilic-Hydrophilic Poly(2-Oxazoline) Block Copolymers as MRI Contrast Agents: From Synthesis to Self-Assembly. *Macromolecules* **2018**, *51* (15), 6047−6056.

(43) Kempe, K.; Lobert, M.; Hoogenboom, R.; Schubert, U. S. Screening the Synthesis of 2-Substituted-2-Oxazolines. *J. Comb. Chem.* **2009**, *11* (2), 274−280.

(44) Harris, J. M.; Bentley, M. D.; Moreadith, R. W.; Viegas, T. X.; Fang, Z.; Yoon, K.; Weimer, R.; Dizman, B.; Nordstierna, L. Tuning Drug Release from Polyoxazoline-Drug Conjugates. *Eur. Polym. J.* **2019**, *109241* DOI: 10.1016/j.eurpolymj.2019.109241.

(45) Cao, H.; Xu, R.; Yu, D. Synthesis and Characterization of 2-Oxazoline-Benzoxazine Compound and Its Polymer. *J. Appl. Polym. Sci.* **2008**, *110* (3), 1502−1508.

(46) Bellamy, L. J. *The Infrared Spectra of Complex Molecules*; Springer: Netherlands, 1980. DOI: 10.1007/978-94-011-6520-4.

(47) Jordan, R.; West, N.; Ulman, A.; Chou, Y. M.; Nuyken, O. Nanocomposites by Surface-Initiated Living Cationic Polymerization of 2-Oxazolines on Functionalized Gold Nanoparticles. *Macromolecules* **2001**, *34* (6), 1606−1611.

(48) Kempe, K.; Rettler, E. F. J.; Paulus, R. M.; Kuse, A.; Hoogenboom, R.; Schubert, U. S. A Systematic Investigation of the Effect of Side Chain Branching on the Glass Transition Temperature and Mechanical Properties of Aliphatic (Co-)Poly(2-Oxazoline). *S. Polymer (Guildf)* **2013**, *54* (8), 2036−2042.

(49) Demirel, A. L.; Tatar Güner, P.; Verbraeken, B.; Schlaid, H.; Schubert, U. S.; Hoogenboom, R. Revisiting the Crystallization of Poly(2-alkyl-2-Oxazoline). *S. J. Polym. Sci., Part B: Polym. Phys.* **2016**, *54* (7), 721−729.

(50) Kourt, M. E.; Fega, E.; Pitsikalís, M. Block Copolymers Based on 2-Methyl- and 2-Phenyl-Oxazoline by Metallocene-Mediated Cationic Ring-Opening Polymerization: Synthesis and Characterization. *Polym. Chem.* **2016**, *7* (16), 2821−2835.