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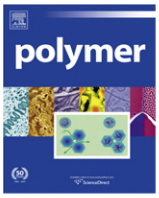

The effect of chemistry on the polymerization, thermo-mechanical properties and degradation rate of poly(β-amino ester) networks

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ABSTRACT

Poly(β-amino ester) networks are gaining attention as a scaffold material for tissue engineering applications where it is important to have tailorable degradation rate and elastic modulus. The objective of this work is to characterize and understand the relationships between chemical structure, polymerization, thermo-mechanical properties, and degradation in poly(β-amino esters) networks. The networks were synthesized from a primary amine with systematically varied molar ratios and chemical structures of diacrylates. Fundamental trends were established between the chemical structure, conversion during polymerization, macromer molecular weight, rubbery modulus, and degradation rate. The thermo-mechanical properties were dependent upon both polymerization steps. The rubbery modulus was tailorable over a range of several MPa by changing molar ratio and diacrylate molecular weight. The degradation rate ranged from hours to months depending upon the composition. Select chemical structures showed degradation rate independent of modulus. This work provides a basis for designing poly(β-amino esters) networks with specific thermo-mechanical properties and degradation rates for biomedical scaffolds.

1. Introduction

Synthetic, biodegradable photopolymerizable networks have potential use in many biomedical applications due to the diverse chemistries available and broad range of mechanical properties. For example, porous poly(propylene fumarate) scaffolds have been proposed for bone applications because of their demonstrated compressive strengths and cytocompatible degradation products [1–4]. In addition, poly(anhydride) networks are currently being developed for injectable *in situ* polymerization for bone defects. These polymers degrade by surface erosion, thus maintaining their mechanical properties longer during the degradation cycle [5–8]. Poly(lactic acid) and its copolymer-based networks have also shown suitable osteoblast viability, controlled mechanical properties, and tailorable degradation [9–12]. Over the past decade, poly(β-amino ester)s (PBAEs) and their networks have gained attention as a biodegradable polymer with biomedical applications, such as non-viral gene delivery and tissue scaffolds [13–17]. It is important to understand the effects of changing the diacrylate to amine ratio and diacrylate molecular weight on the polymerization because this will subsequently affect the degradation rate and thermo-mechanical properties.

The synthesis of PBAE networks is a multi-step process where the step-growth polymerization of macromers is a conjugate addition of the primary amine to diacrylate, followed by a free-radical UV-photopolymerization for network formation, and subsequent hydrolytic degradation as illustrated in Fig. 1. The molar ratio of diacrylate to amine is kept greater than 1:1 to insure acrylate endgroups for photopolymerization. There are several benefits to the synthesis of this material including no byproduct formation and the ability to spatially and temporally control the network formation. Initial compositions have been quickly expanded upon by using commercially available monomers to provide a structurally diverse library of materials [18–20]. Previous studies have shown that after the step-growth polymerization, the maximum macromer molecular weight is achieved at a 1:1 ratio of diacrylate to amine ratio. With the aid of a semi-automated process, a large library of poly(β-amino esters) were created, and their modulus and degradation rates evaluated. A range of properties for these networks was reported where degradation profiles showed a range from less than 24 h to over 90 days and the elastic modulus ranged from 4 to 350 MPa [21].

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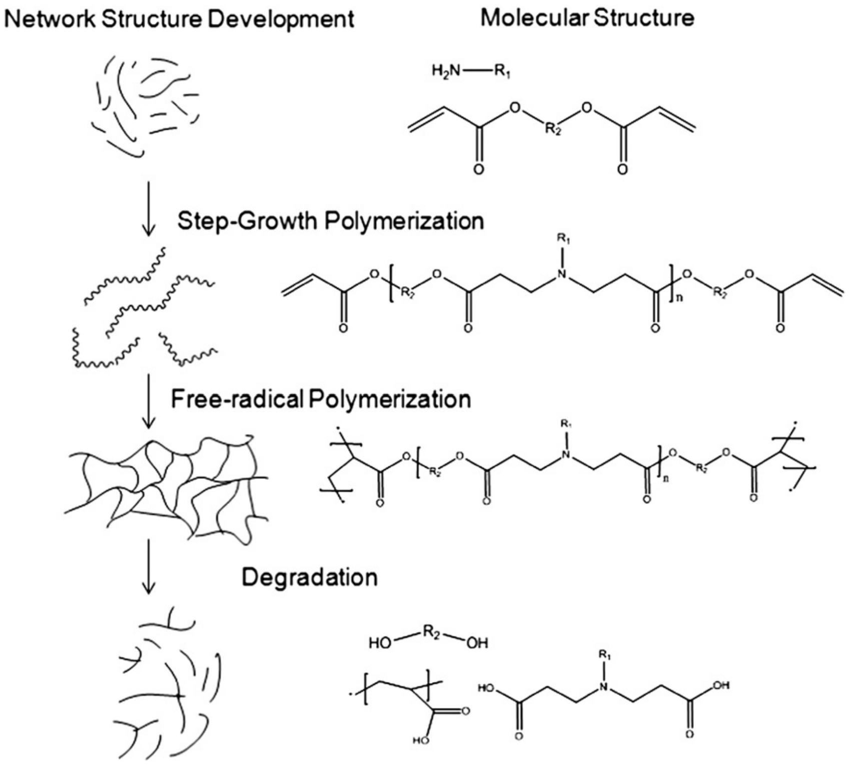

Fig. 1. Development and degradation of Poly(β-amino ester) networks.

More recently, the effect of the molar ratio on the macromer molecular weight and mechanical properties has been studied. Lower macromer molecular weight mixtures tend to react quicker than high macromer molecular weight mixtures and reach higher double bond conversions because the higher macromer molecular weight mixtures have a lower concentration of double bond reactive groups and are more limited in diffusion. In addition, the sol fraction has been shown to decrease as molar ratio increases, thus supporting the lack of conversion at low ratios. Since the macromer molecular weight decreases as ratio increases, the crosslinking density increases, thus the modulus increases [15]. This has been further explored by adding a trifunctional crosslinker, which increases the modulus via increased crosslinking density [16]. Although molar ratio has been shown to affect the modulus, it is unknown how changing the molar ratio in combination with diacrylate molecular weight affects modulus and degradation rate.

The purpose of this study is to determine the effect of the diacrylate molecular weight and chemistry on the polymerization, thermo-mechanical properties, and degradation profiles of a model group of poly(β-amino esters). The effect of diacrylate molecular weight on polymerization is revealed through systematic variation of diacrylate molecular weight at constant molar ratio. Networks with varying molar ratio and diacrylate chemistry are studied in order to ascertain the influence of the diacrylate on the thermo-mechanical properties. The effect of diacrylate chemistry on degradation rate is studied by comparing poly(ethylene glycol) diacrylate based networks to diol diacrylate based networks.

2. Experimental

2.1. Materials

Poly(ethylene glycol) diacrylate (PEGDA) of four varying molecular weights, $M_n \sim 258$, 302, 575, 700, was used as one diacrylate system. The other diacrylate system, diol diacrylates (DDA), consisted of 1,4-butanediol diacrylate (DDA198) (Dajac Labs), 1,6-hexanediol diacrylate (DDA226), 1,9-nonanediol diacrylate (DDA268) (TCI). The primary amine was 3-methoxypropylamine (3MOPA). 2-hydroxy-1-[4-(hydroxyethoxy)phenyl]-2-methyl-1-propanone (Irgacure 2959) was used as the photoinitiator. All chemicals were used as received from Sigma Aldrich unless otherwise noted.

2.2. Methods

2.2.1. Polymerization

Each of the seven diacrylates was mixed with 3MOPA at molar ratios from 1.05:1 to 1.25:1 at increments of 0.05. The step-growth polymerization occurred for 24 h at 200 rpm at 90 °C on a JKEM reaction block (RBC-20 with BTS-1500 shaker) to form the macromers. The resulting macromers were either stored at 4 °C or mixed with 0.5 weight percent (wt.%) Irgacure 2959 for photopolymerization. The macromers were placed into a 5 cm × 6 cm × 0.1 cm teflon mold, sealed with glass slides, and polymerized for 10 min by a UVP Blakray lamp ($\sim$8 mW/cm^2) to form chemically crosslinked networks. Due to the inherent heterogeneity, the materials were synthesized and all tested in triplicate, where mean ± SD is reported.

2.2.2. Thermo-mechanical properties

Dynamic mechanical analysis (DMA) of each network was performed via a TA Instruments DMA Q800. Rectangular samples were run in tension under strain control of 0.1% according to the following protocol: equilibrate at -100 °C, isotherm for 2 min, ramp 3 °C per minute to 100 °C. The glass transition temperature (T_g) was defined at the peak of the tan δ curve. The molecular weight between crosslinks was calculated from Equation (1), where E is the modulus, ρ is the polymer density, R is the gas constant, T is the temperature in Kelvin, and M_c is the molecular weight between crosslinks [22].

$$M_c = \frac{3\rho RT}{E} \tag{1}$$

2.2.3. *Differential scanning calorimetry (DSC)*

Select networks were analyzed with a TA Instruments DSC Q100. Samples were cooled at 3 °C per minute to −90 °C, isotherm for 2 min, and then heated at 3 °C per minute to 100 °C.

2.2.4. *^{1}H Nuclear magnetic resonance spectroscopy*

A Varian Mercury Vx 400 ^{1}H NMR was used to verify the structures of the macromers after step-growth polymerization in deuterated chloroform. The spectrum was analyzed via MestRe-C software to determine the number of hydrogen as well as an estimate of the diacrylate to amine ratio, and therefore the molecular weight [15].

2.2.5. *Fourier transform infrared spectropscopy*

A Nicolet Nexus 870 FTIR with attenuated total reflectance (ATR) module was used to characterize the step-growth and free-radical polymerization. Macromer samples were taken at 2, 4, 8, 16, and 24 h from the reaction block and the acrylate peak at 812 cm^{-1} was monitored [23]. After 24 h, the samples were mixed with 0.5 wt.% Irgacure 2959 and polymerized with the UVP Blakray lamp. The data collection was taken in real time for at least 5 min to ascertain the degree of conversion to a network from the peak at 812 cm^{-1}.

2.2.6. *Sol fraction*

A sol fraction test was employed to determine the extent of conversion in network formation. Tert-butyl benzene was used, where 1 cm^2 squares cut from 1 mm thick sheets were soaked for 48 h with a change in solvent at 24 h. The samples were dried in an oven with dessicant to remove all traces of solvent and then allowed to equilibrate with the surrounding atmosphere for 3 days. The sol fraction is defined through Equation (2), where M_f is the final mass and M_i is the initial mass.

$$\text{Sol Fraction} = 1 - \frac{M_f}{M_i} \tag{2}$$

2.2.7. *Degradation and swelling*

In order to determine the degradation rate and water content of each material, each material was soaked for varying amounts of time. Each material was cut from a 1 mm thick sheet into a 1 cm^2 square and placed into a well plate with phosphate buffered saline (PBS), pH 7.4. The well plates remained in an incubator at 37 °C on a rotary shaker at 60 rpm. Samples were patted dry to remove excess water to obtain the wet sample mass. The samples were dried for 24 h and the mass taken. The water content of each material will be defined by Equation (3), where M_{wi} is the wet mass at time *i* and M_{di} is the mass at time *i* after 24 h of drying. The mass loss will be defined by Equation (4), where M_{di} has been previously described and M_o is the initial mass.

$$\text{Water Content} = \frac{M_{wi}}{M_{di}} - 1 \tag{3}$$

$$\text{Mass Loss} = 1 - \frac{M_{di}}{M_o} \tag{4}$$

3. Results

3.1. *Thermo-mechanical properties*

Representative DMA and DSC curves are shown in Fig. 2 for both PEGDA and DDA networks. The glass transition temperature (T_g) is well below room temperature for all these materials, and thus the material is rubbery at ambient temperatures. PEGDA700-based networks have a hump in the modulus above T_g, which signifies crystallization and subsequent melting due to the high molecular weight of the PEGDA chain. The crystallization and melting can be seen in the DSC curves in Fig. 2B for the PEGDA700-based network. The molecular weight of the PEGDA575-based network or the DDA226-based network is not high enough to promote crystallization, thus the lack of the hump in the DMA curves of Fig. 2A and the lack of crystallization and melting peaks in the DSC curves of Fig. 2B.

Networks formed from each diacrylate and 3MOPA at varying molar ratios were tested on the DMA. The modulus in the rubbery regime at a temperature of T_g+75 °C is given as a function of the molar ratio as shown in Fig. 3A and B. In order to compare rubbery modulus between systems, the rubbery modulus was measured at the same relative temperature to T_g, T_g+75 °C. The PEGDA 302 does not form a network at molar ratio 1.05:1 due to a lack of acrylate bonds. The modulus ranged from 0.14 to 5.36 MPa for the PEGDA networks, and from 0.15 to 6.71 MPa for the DDA networks. The rubbery modulus increases as the molar ratio increases, as expected from a similar study [15]. However, there is no obvious trend between the diacrylate molecular weight and the rubbery modulus. The T_g as a function of the molar ratio is shown in Fig. 3C and D. The T_g ranged from −44.3 °C to −31 °C for the PEGDA networks, and from −50.9 to −35.6 °C for the DDA networks. The T_g increases as the molar ratio increases and as the diacrylate molecular weight decreases for the DDA networks, but the T_g increases only as the diacrylate molecular weight decreases for the PEGDA networks. The molecular weight between crosslinks for PEGDA-based and DDA-based networks for each molar ratio is shown in Fig. 3E and F. The molecular weight between crosslinks ranged from 1500 to 115,000 g/mol for the PEGDA-based networks and from 1200 to 59,000 g/mol for the DDA-based networks.

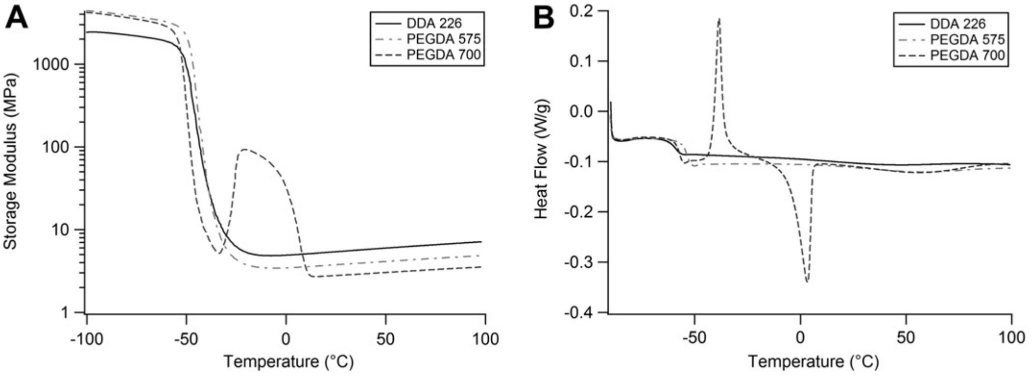

Fig. 2. DMA curves of poly(β-amino ester) networks (A). DSC curves of poly(β-amino ester) networks (B).

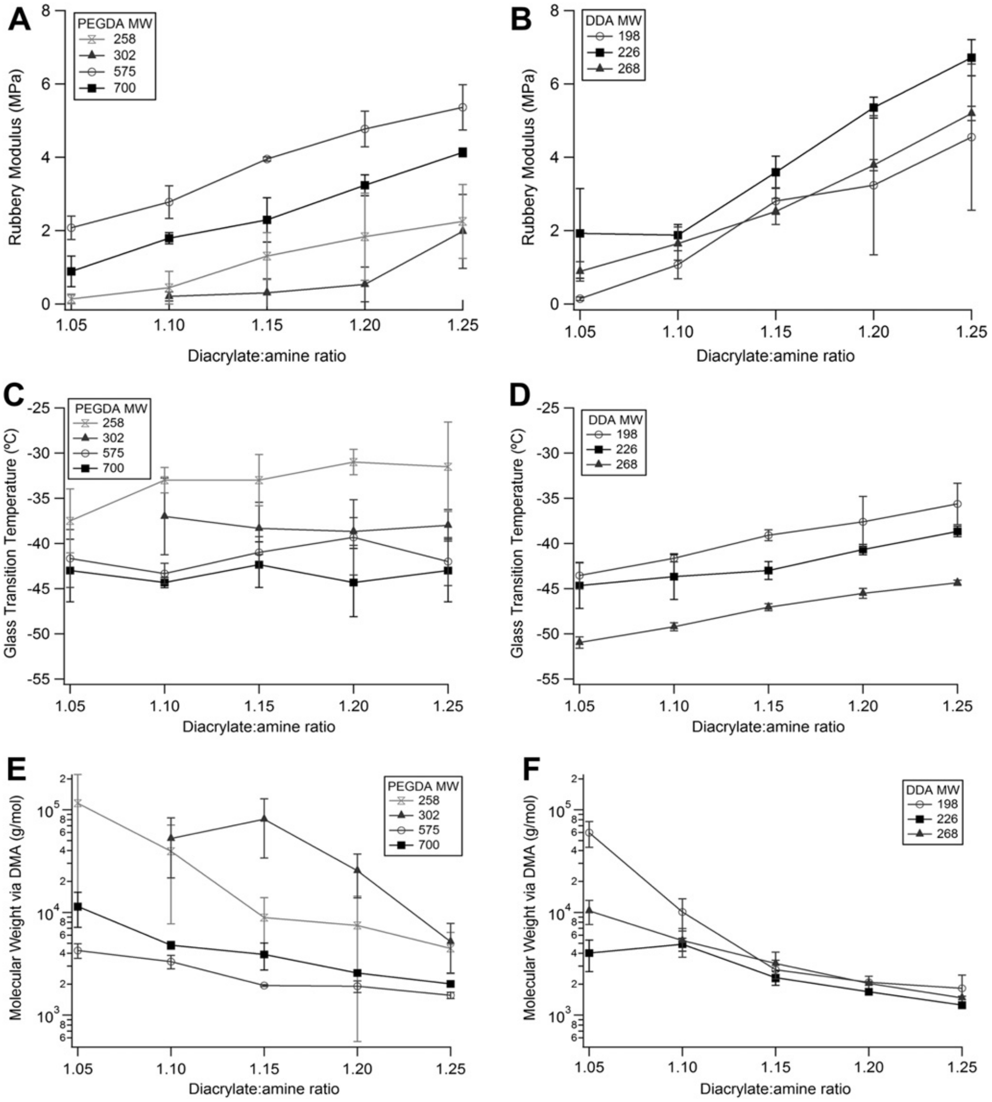

Fig. 3. Rubbery modulus and T_g as a function of molar ratio for each network. Rubbery modulus of PEGDA-based networks (A) and DDA-based networks (B) at a temperature of T_g+75 °C by DMA. T_g of PEGDA-based networks (C) and DDA-based networks (D). The molecular weight between crosslinks for PEGDA-based networks (E) and DDA-based networks (F).

3.2. Step-growth polymerization

A series of structural analyses were performed to help understand the trends in modulus presented in Fig. 3. In order to understand the extent of conversion during step-growth polymerization, the acrylate bond was monitored via FTIR over 24 h. The molar ratio of 1.20:1 was examined for each diacrylate as shown in Fig. 4. In Fig. 4A, the PEGDA258 and PEGDA302 converted quicker and to a higher extent than the PEGDA575 and the PEGDA700 networks. In Fig. 4B, the degree and rate of conversion increased as the DDA molecular weight decreased. PEGDA and DDA macromers formed from monomers of similar molecular weight have quite different step-growth conversions, where PEGDA monomers converted faster and to a higher degree. Due to the diacrylate to amine ratio being greater than 1, all of the diacrylate endgroups will not be completely consumed. When using a molar ratio of 1.20:1 of diacrylate to amine and all of the amine endgroups react, there will be a theoretical diacrylate excess of 16.6%; thus, the expected amount of diacrylate endgroups consumed is 83.3%.

After 24 h of step-growth polymerization, NMR was used to verify the chemical structure of the macromers, especially the presence of acrylate endgroups, and the incorporation of the amine into the macromer as shown in Fig. 5 by an absence of a peak near 1 ppm. From endgroup calculations, an estimation of macromer molecular weight can be determined. The average molecular weight of the macromers from NMR for each backbone chemistry and molar ratio is shown in Fig. 6. The average molecular weight of the macromers decreased as the molar ratio increased for both network chemistries. The macromer molecular weight ranged from 2200 to 37,400 g/mol for the PEGDA-based macromers, and the macromer molecular weight of the DDA-based macromers ranged from 1700 to 11,800 g/mol. The macromer molecular weight of the PEGDA-based macromers showed no direct relationship with diacrylate molecular weight, where the PEGDA575 and PEGDA258-based macromers had similar macromer molecular weights and the PEGDA700 and the PEGDA302-based macromers had similar macromer molecular weights. The PEGDA258 and PEGDA302-based macromers did reach a higher conversion during step-growth, and therefore have higher macromer molecular weight.

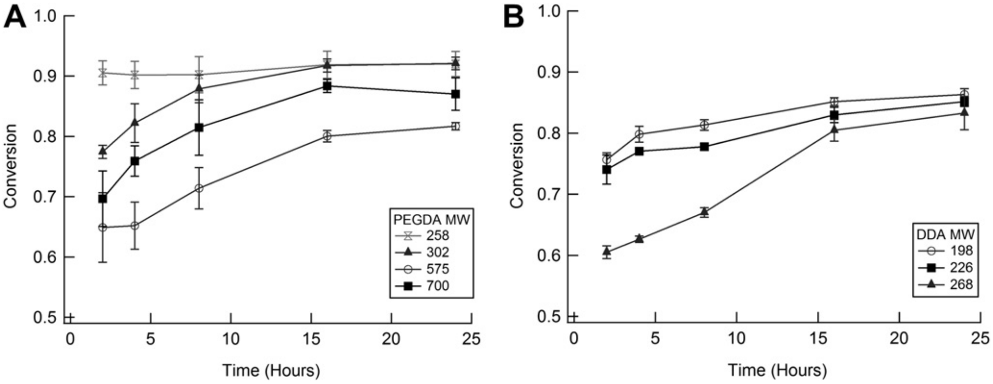

Fig. 4. Conversion as a function of time for PEGDA macromers of 1.20:1 M ratio (A) and DDA macromers of 1.20:1 M ratio (B) as measured by FTIR.

The macromer molecular weight of DDA-based macromers converged as the molar ratio increased.

3.3. *Photopolymerization*

From the FTIR-ATR photopolymerization, the conversion of remaining acrylate bonds was monitored for networks at a molar ratio of 1.20:1. The conversion of PEGDA networks and DDA networks is shown in Fig. 7A and B, respectively. PEGDA575 and PEGDA700 networks reached high degrees of conversion, while PEGDA258 and PEGDA302 did not. The DDA226 and DDA268 reached higher degrees of conversion than the DDA198 network. In essence, the networks formed from macromers that had high degrees of conversion during step-growth did not reach high degrees of conversion during photopolymerization.

To compare the conversion measured from FTIR-ATR photopolymerization, sol fraction testing was conducted across all molar ratios and diacrylate monomer chemistries and molecular weights as shown in Fig. 8. PEGDA575 and PEGDA700 networks showed lower sol fractions, 0.03–0.06, respectively, compared to the PEGDA258 and PEGDA302 networks, 0.13–0.5, respectively. DDA networks showed similar levels of sol fraction to the PEGDA networks ranging from 0.04 to 0.38.

3.4. *Degradation and water content*

Degradation profiles for all diacrylate molecular weights and molar ratio of DDA are shown in Fig. 9A. The degradation rates of the DDA226 and DDA268 are tightly grouped, while the DDA198 is distinct from the other DDA networks. The marked curves are the lowest molar ratio, 1.05:1, for each DDA molecular weight. The water content of the DDA226 and DDA268 does not exceed 1, while the water content of the DDA198 is higher as shown in Fig. 9B. The networks with rapid degradation match the networks with high water content. In the DDA system degradation rate is strongly

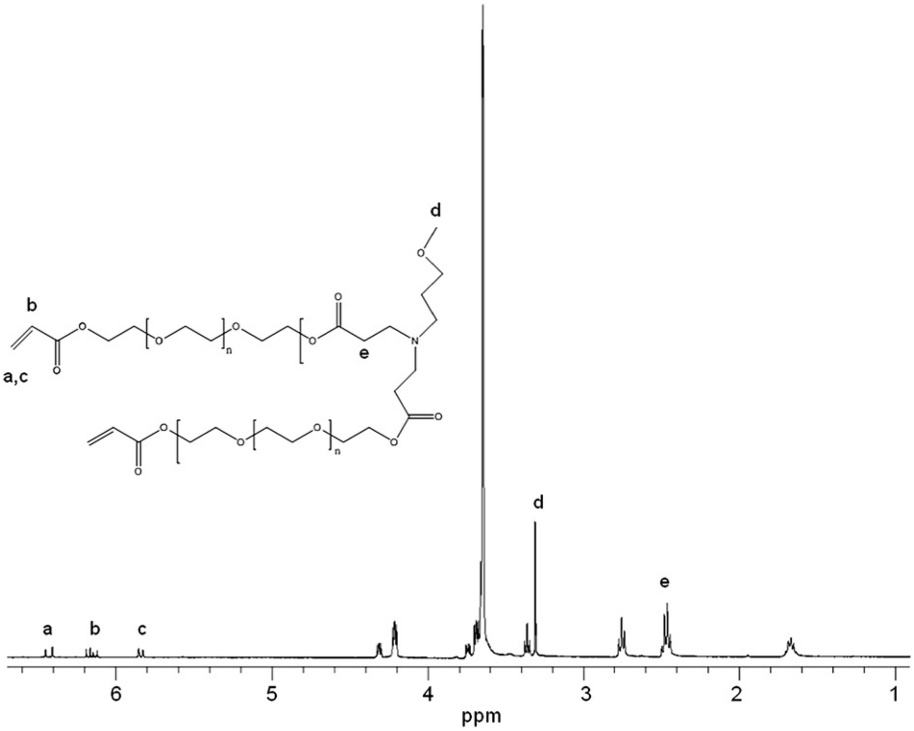

Fig. 5. An exemplary NMR spectra of PEGDA575-based macromer, molar ratio 1.25:1. Corresponding letters (a–e) of the peaks to the structure are given, where a-c define the acrylate endgroup, d defines the terminal methyl group of the amine, and e defines a bond that was previously unsaturated.

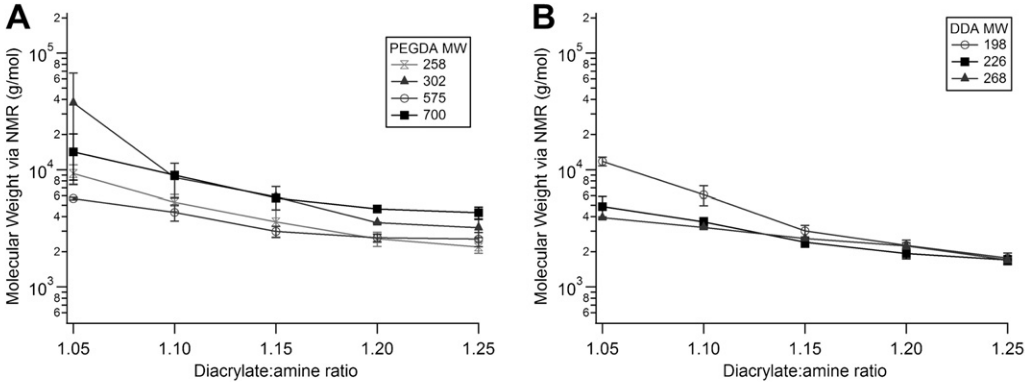

Fig. 6. The molecular weight of macromers determined from NMR for PEGDA-based networks (A) and DDA-based networks (B).

influenced by molecular weight but not by ratio for this range of molecular weights.

The degradation profiles of PEGDA-based materials are presented in Fig. 10A and B. The degradation profiles for PEGDA700 networks for the 5 different molar ratios are shown in Fig. 10A. The lower PEGDA700 ratios degraded rapidly, while the higher ratios lasted for at least 24 h. The degradation profiles for all PEGDA networks at a ratio of 1.10:1 and 1.25:1 are shown in Fig. 10B. All PEGDA networks at a ratio of 1.10:1 degraded completely within 8 h, while the networks at a ratio of 1.25:1 lasted 12 h or more. The water contents for the four PEGDA networks at a ratio of 1.25:1 are shown in Fig. 10C. The networks with high initial water contents match the networks with rapid degradation.

4. Discussion

In this study, the effect diacrylate molecular weight, diacrylate to amine ratio, and diacrylate chemistry on PBAE network properties was explored. The results show that the degradation rate and thermo-mechanical properties are greatly influenced. The two systems, PEGDA-based and DDA-based, were selected for their different history of use and their diverse chemical properties. From a biocompatibility standpoint, PEGDA-based polymers are known for their biocompatibility, and the degradation product containing 3MOPA has yet to be proven harmful. In addition, PEGDA-based systems were chosen due to previous testing of their mechanical properties under cyclical loading [24]. As a comparison, DDA-3MOPA systems were chosen to study the effect of changing the backbone chemistry from hydrophilic to hydrophobic on the thermo-mechanical properties and degradation. The molar ratio range was limited to 1.25:1 to prevent non-degradable crosslinks from forming from excess pure diacrylate. Prior work has demonstrated that the elastic modulus of the network is affected by changes in macromer molecular weight by varying the molar ratio. Here we explore the impact of diacrylate molecular weight and chemistry on step-growth polymerization, photopolymerization, and subsequent properties.

Dynamic mechanical analysis was used as a screening method in order to look at a range of networks of varying crosslinking density and chemistry. A commonality between all these materials is their low T_g, as shown by the large drop in storage modulus in Figs. 2 and 3C and D. The low T_g is due to the lack of steric hindrance usually created from bulky, rigid side groups, and the enhanced flexibility from the ethylene glycol, methylene, or amine groups incorporated into the backbone. Thus, by increasing the diacrylate molecular weight, more flexible groups are being incorporated resulting in the subsequent decrease in T_g. In addition, varying the molar ratio and diacrylate molecular weight and chemistry produced a broad range of rubbery moduli. The rubbery modulus increases as molar ratio increases, thus the crosslinking density increases as the macromer molecular weight decreases due to the increasing molar ratio as shown in Fig. 3A and B. However, the trends in elastic modulus with diacrylate molecular weight were less obvious and non-monotonic. Low molecular weight diacrylates may be expected to create denser networks, thus having a higher modulus. However, in Fig. 3A, the low molecular weight diacrylates had lower rubbery moduli or in Fig. 3B, the low and high molecular weight diacrylates had similar rubbery moduli. The crystallization and melting of PEGDA700-based networks was not expected, but is possible as the network structure has passed above its T_g in Fig. 2. It also defines a molecular weight boundary, where PEGDA-based networks do not crystallize when PEGDA is below 700 g/mol. Because of these unexpected

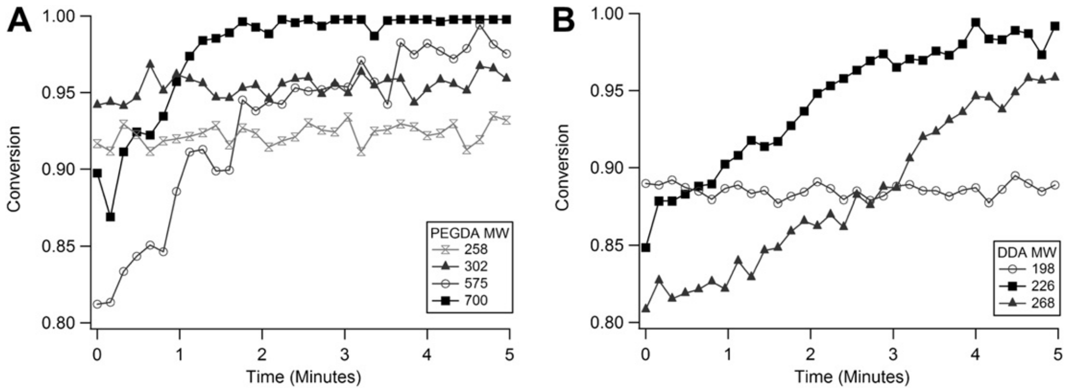

Fig. 7. UV-photopolymerization monitored by FTIR-ATR for PEGDA networks (A) and DDA networks (B).

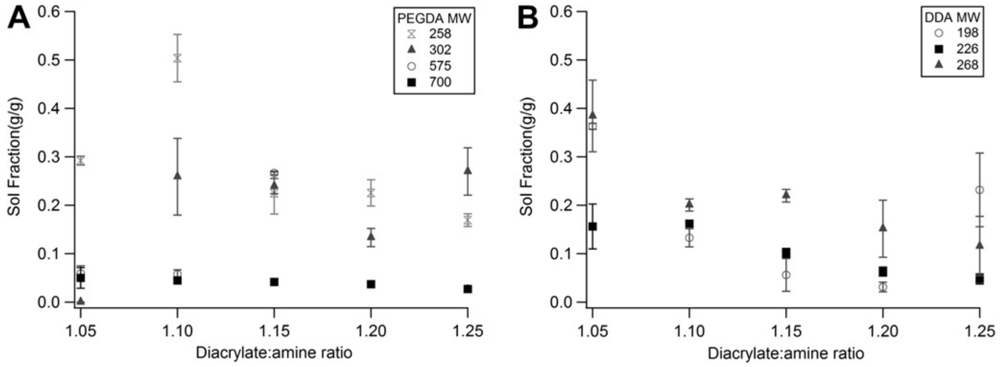

Fig. 8. Sol fraction for all compositions for PEGDA networks (A) and DDA networks (B).

trends in modulus, a further understanding of both polymerization steps was explored to understand the relation between diacrylate molecular weight and network modulus.

The step-growth polymerization of PEGDA-based networks and DDA-based networks was studied by varying the diacrylate molecular weight and chemistry while maintaining a constant molar ratio of 1.20:1. The networks synthesized from lower molecular weight diacrylates, such as PEGDA258 and PEGDA302, converted to a higher degree and at a faster rate than their higher molecular weight PEGDA counterparts. The increase of diacrylate molecular weight decreases the monomer's mobility thus decreasing the rate and degree of conversion. With a molar ratio of 1.20:1, the conversion would have been expected to be equivalent for all PEGDA-based macromers. The higher degree of conversion for the PEGDA258 and PEGDA302-based macromers may have resulted from termination during the step-growth polymerization from monomers having only one acrylate endgroup instead of two or cyclization of the diacrylate to amine. PEGDA monomers have near 14% impurities comprised of poly(ethylene glycol) chains and monofunctional poly(ethylene glycol) acrylate, where over 10% may be monofunctional poly(ethylene glycol) acrylate [25]. DDA monomers have near 10% impurities, where 3% comprises the monofunctional diol acrylate [26]. These monofunctional acrylate impurities will terminate the step-growth reaction early producing smaller molecules without any acrylate functionality or cause dangling ends which would not be elastically effective. The DDA-based networks' rates and degrees of conversion decreased as the diacrylate molecular weight increased again due to decreased mobility. The effect of decreasing rate and degree of conversion as diacrylate molecular weight increases is in agreement with hyperbranched amine-acrylate systems [27]. The macromer molecular weight post-step-growth polymerization is a key determinant of the crosslinking density and thus the rubbery modulus. NMR can provide an estimate based upon the ratio of acrylate endgroups to amine groups and may count cyclization and dangling groups with only one acrylate endgroup. By using NMR, the macromer molecular weight can be compared to the elastically effective molecular weight between crosslinks via DMA. Figs. 3F and 6B show similar molecular weights for the DDA-based networks, thus they are converting ideally and elastically effective chains are the majority of the chains present. PEGDA575 and PEGDA700-based networks also show similar molecular weights in Figs. 3E and 6A. The PEGDA258 and PEGDA302-based networks have a drastic difference, where the molecular weight via DMA is much higher. Thus, the step-growth polymerization is producing elastically ineffective chains, which would be comprised of a combination of dangling chains and cycles of low molecular weight as seen in the molecular weight via NMR. The low molecular weight diacrylates are more likely to form cycles as seen in kinetic models and other diacrylate systems, which lowers the formation of crosslinks, thus lowering their modulus [28,29]. By comparing the repeating unit structure of DDA and PEGDA, PEGDA is the more flexible monomer based on its lower characteristic ratio, where poly(ethylene glycol) and polyethylene have characteristic ratios of 5.6 and 7.4, respectively [30]. This increase in flexibility at nearly the same molecular weight may contribute to the increased cyclization. Because the step-growth polymerization determines the macromer molecular weight and the degree of acrylate conversion, this step will also affect the subsequent polymerization, as will be further discussed.

The second polymerization, the UV-photopolymerization, is responsible for network formation. A critical population of acrylate

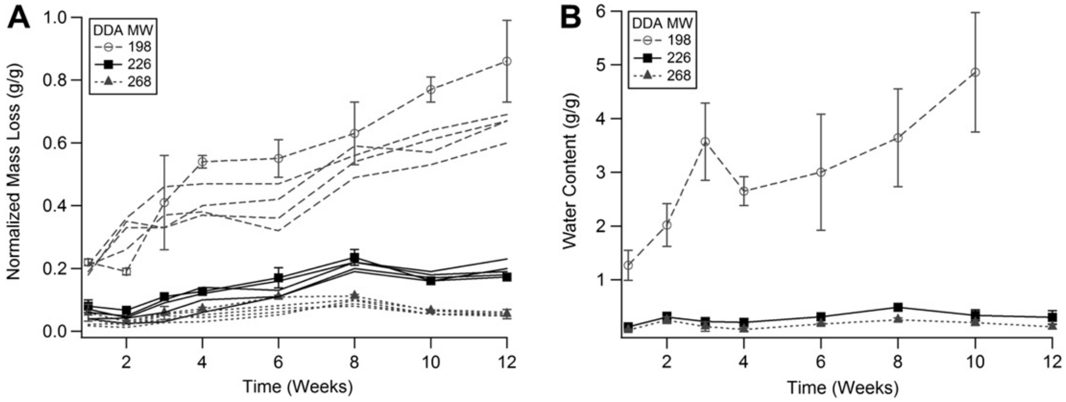

Fig. 9. Degradation profile for all diacrylate molecular weights of DDA and all molar ratios. The molar ratio of 1.05:1 is displayed by markers and the remaining curves represent the behavior of the other 4 M ratios (9A) at each molecular weight and water content profile for the DDA networks at a molar ratio of 1.05:1 (9B).

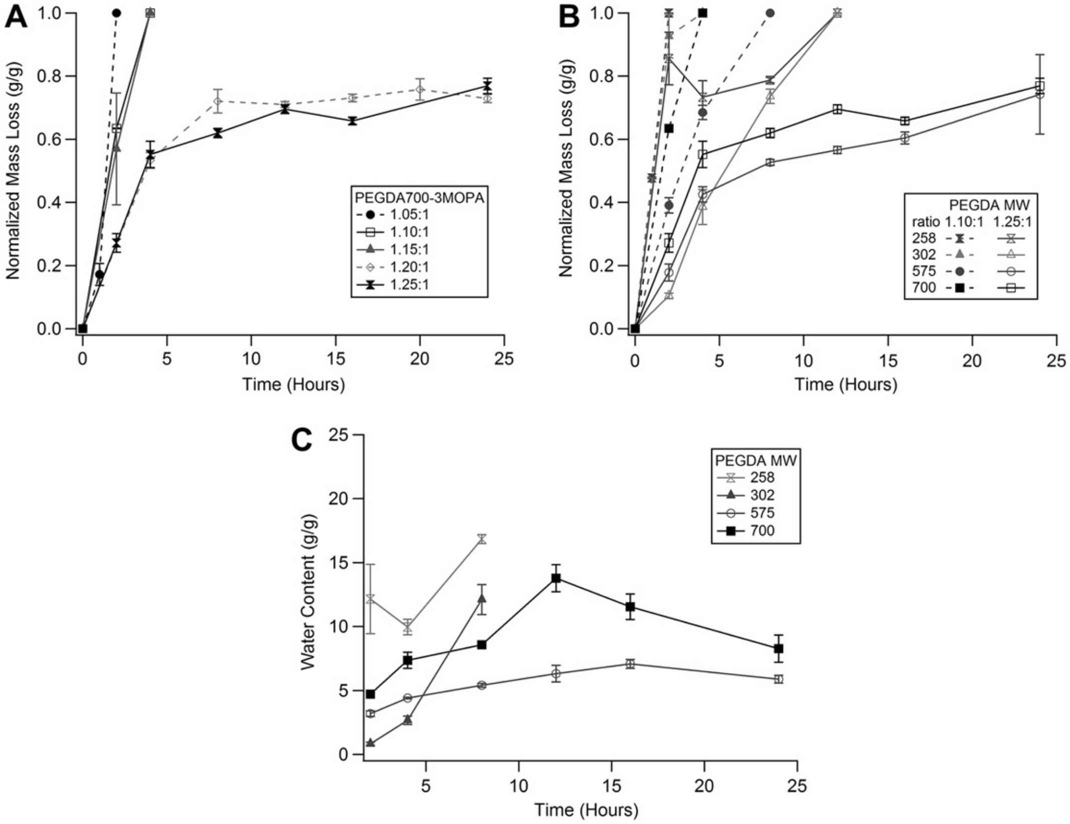

Fig. 10. Degradation profiles for PEGDA700 at all molar ratios (10A). Degradation profiles for all PEGDA networks at molar ratios at 1.10:1, filled markers, and 1.25:1, open markers (10B). Water content profiles for PEGDA networks at a ratio of 1.25:1 (10C).

endgroups is necessary for full network formation. The networks that reached high degrees of photopolymerization were the macromers that did not reach high levels of conversion during their step-growth polymerization. Thus because the PEGDA575 and PEGDA700-based networks reached high levels of photopolymerization conversion, they formed more complete networks and obtained higher rubbery moduli. By examining the macromer molecular weight in combination with the degree of conversion, the arrangement of rubbery moduli in Fig. 3A is made clear. The PEGDA258 and PEGDA575-based networks have nearly different degrees of photopolymerization, and thus possess differing rubbery moduli. Both DDA226 and DDA268-based networks converted to a higher degree during photopolymerization, but DDA226-based network has a lower macromer molecular weight than the DDA268, and thus formed networks with higher rubbery moduli compared with DDA268. The DDA198 converted to a lesser degree during photopolymerization, but still reached similar values of rubbery moduli as the DDA268. The results from the sol fraction, an alternative method of measuring network conversion, are in good agreement with the FTIR-ATR photopolymerization and the rubbery moduli. The networks suspected of having dangling endgroups and cycles, PEGDA258 and PEGDA302-based networks, had the highest sol fractions, thus this lack of network formation further decreased their modulus values.

The results of this study show that the effect of diacrylate molecular weight and chemistry on the polymerization and mechanical properties can only be fully understood only by considering structure after both the step-growth polymerization and photopolymerization. If the macromers do not reach high conversion during step-growth but obtain a high degree of conversion during photopolymerization, then the effect of diacrylate molecular weight on rubbery moduli can be understood from the macromer molecular weight. If two macromers have the same macromer molecular weight via NMR but convert differently during photopolymerization, then the degree of conversion during photopolymerization will dictate rubbery modulus. The step-growth polymerization controls the degree of acrylate conversion necessary for network formation and the macromer molecular weight that influences crosslinking density. The photopolymerization controls network formation, but is greatly influenced by the amount of acrylate endgroups remaining from the step-growth polymerization.

The degradation profiles and water content of the networks are controlled by two different mechanisms. The degradability of DDA-based networks are affected by their diacrylate molecular weight as can be seen in Fig. 9A. All five molar ratios of DDA226 and DDA268 have nearly the same degradation profile, and the 5 M ratios of DDA198 are similar and distinct from the DDA226 and DDA268 networks. It is clearly seen that as the diacrylate molecular weight increases, the degradation rate decreases due to a decrease in water content as shown in Fig. 9B. The water content follows the same trend as the degradation profiles, where the number of methylene units or the diacrylate molecular weight is the controlling factor. The independence of degradation rate from molar ratio, thus rubbery modulus is unexpected because increasing the crosslinking density typically alters the degradation rate.

Unlike the DDA-based networks, the PEGDA-based networks' degradation profiles are controlled less by their diacrylate molecular weight, and more by their molar ratio. The low molar ratios networks are lightly crosslinked thus allowing for large amounts of water to enter the network, which leads to rapid degradation. The higher molar ratios of 1.20:1 and 1.25:1 plateau due to the formation of non-degradable crosslinks and a higher network density. All PEGDA-based networks follow the same trend, regardless of the diacrylate molecular weight. All PEGDA-based networks eventually had water content greater than 500% by the time of full degradation, which is the main cause for their rapid degradation. The dual mechanisms illustrate the difference in backbone chemistry of the diacrylates. Degradation in the DDA-based networks is more controlled by diacrylate molecular weight while degradation in the PEGDA-based networks is dominated by molar ratio. This separation of degradation rate and modulus for the DDA-based networks is significant, where it will allow for enhanced tailoring of these networks for tissue scaffolds and drug release devices.

5. Conclusion

In this study, PBAEs networks were synthesized through step-growth and photopolymerization reactions. The rubbery modulus was affected by the macromer molecular weight and the acrylate endgroup conversion during the step-growth polymerization, and by the degree of network formation during photopolymerization. The lack of high conversion during step-growth polymerization is essential for full conversion during photopolymerization. The diacrylate molecular weight influences the rate and degree of conversion during step-growth polymerization, thus affecting the subsequent polymerization. The degradation rate for DDA is dependent on the diacrylate molecular weight, and independent of the molar ratio, thus independent of the modulus. The degradation rate for PEGDA networks is dependent on the molar ratio, where as ratio increases the time to complete degradation increases. This understanding of how the two step polymerization of poly(β-amino ester) networks affects the mechanical properties and degradation will allow for the precise tailoring of poly(β-amino ester) networks for future biomedical applications.

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References

[1] Fisher JP, Holland TA, Dean D, Engel PS, Mikos AG. J Biomat Sci Polym Ed 2001;12:673–87.
[2] Fisher JP, Holland TA, Dean D, Mikos AG. Biomacromol 2003;4:1335–42.
[3] Fisher JP, Timmer MD, Holland TA, Dean D, Engel PS, Mikos AG. Biomacromol 2003;4:1327–34.
[4] He S, Timmer MD, Yaszemski MJ, Yasko AW, Engel PS, Mikos AG. Polymer 2001;42:1251–60.
[5] Burkoth AK, Anseth KS. Biomaterials 2000;21:2395–404.
[6] Burkoth A, Burdick J, Anseth KS. J Biomed Mater Res 2000;51:352–9.
[7] Muggli DS, Burkoth AK, Anseth KS. J Biomed Mater Res 1999;46:271–8.
[8] Anseth KS, Shastri VR, Langer R. Nat Biotechn 1999;17:156–9.
[9] Burdick J, Mason M, Anseth KS. J Biomat Sci Polym Ed 2001;12:1253–65.
[10] Burdick J, Philpott L, Anseth KS. J Polym Sci Part A: Polym Chem 2001;39:683–92.
[11] Davis KA, Burdick J, Anseth KS. Biomaterials 2003;24:2485–95.
[12] Elisseeff J, Anseth KS, Langer R, Hrkach JS. Macromolecules 1997;30:2182–4.
[13] Akinc A, Anderson DG, Lynn DM, Langer R. Bioconjugate Chem 2003;14:979–88.
[14] Akinc A, Lynn DM, Anderson DG, Langer R. J Am Chem Soc 2003;125:5316–23.
[15] Brey DM, Erickson I, Burdick J. J Biomed Mater Res Part A 2008;85A:731–41.
[16] Brey DM, Ifkovits JL, Mozia RI, Katz JS, Burdick J. Acta Biomater 2008;4:207–17.
[17] Jere D, Yoo M, Arote R, Kim T, Cho M, Nah J, et al. Pharm Res 2007;25:875–85.
[18] Anderson DG, Lynn DM, Langer R. Angew Chem 2003;42:3153–8.
[19] Lynn DM, Anderson DG, Putnam D, Langer R. J Am Chem Soc 2001;123:8155–6.
[20] Lynn DM, Langer R. J Am Chem Soc 2000;122:10761–8.
[21] Anderson DG, Tweedie CA, Hossain N, Navarro SM, Brey DM, Vliet KJV, et al. Adv Mater 2006;18:2614–8.
[22] Pascault J, Sautereau H, Verdu J, WIlliams RJJ. Thermosetting polymers. New York: Marcel Dekker; 2002.
[23] Senyurt AF, Wei H, Hoyle CE, Piland SG, Gould TE. Macromolecules 2007;40:4901–9.
[24] Keim T, Gall K. J Biomed Mater Res Part A 2009;92:702–11.
[25] Peters R, Litvinov VM, Steeman P, Dias AA, Mengerink Y, van Benthem R, et al. J Chromatogr A 2007;1156:111–23.
[26] Kanerva L. Acta Odontol Scand 2001;59:320–9.
[27] Hobson LJ, Feast WJ. Polymer 1999;40:1279–97.
[28] Kannurpatti AR, Anseth JW, Bowman CN. Polym Degrad Stab 1998;39:2507–13.
[29] Elliott JE, Bowman CN. Polym React Eng 2002;10:1–19.
[30] Hiemenz PC, Lodge TP. Polymer chemistry. Boca Raton: CRC Press; 2007.