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Degradation Kinetics of Photopolymerizable Poly(lactic acid) Films

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ABSTRACT: A series of acrylic poly(lactic acid) (PLA) films were produced via photopolymerization. Enzymatic degradation of the films was investigated by submerging or spraying the films with a solution of proteinase K, *Chromobacterium viscosum* (CvL), *Rhizomucor miehei* (RmL), or *Candida cylindracea* (CcL). Degradation was monitored by titration of the carboxylic acid groups, MS, and MS/MS. It was found that the degradation rate of the films was dependent on the water uptake of the film and enzyme solution used. The highest degradation rates, for both systems, were obtained by use of a proteinase K solution. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40475.

KEYWORDS: degradation; photopolymerization; films

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INTRODUCTION

The use of biomaterials as polymers is very advantageous because their mechanical and degradation properties can be tailored to meet specific end usages.[1–10] Among all the polymer families, polyesters offer advantages for use in biomaterials over other polymers due to the ability of polyesters to be degraded through hydrolysis of ester linkages and the fact that the degradation byproducts of many of these polymers can be absorbed through metabolic pathways.[3] Out of all the polyesters, poly(lactic acid) (PLA) is one of the most used in environmental and biological degradable systems.[3,11–15]

The degradation of PLA has been investigated by many groups,[16–24] in particular, proteinase K from *Tritirachium album* has been shown to be an excellent enzyme for the degradation of PLA and its copolymers.[16–19] Enzymatic degradation of PLA has been shown to increase with decreasing crystallinity[16–18] and/or by increasing the hydrophilicity of the material.[17,25,26] The ability to alter hydrophilicity and degradation properties of films containing PLA has been investigated by multiple researchers through the production of various block copolymers.[25,27–38] Increasing the hydrophilicity of a polymer increases the degradation of the material due to the fact that degradation can occur through the bulk of the material; otherwise, for a hydrophobic polymer, degradation will be limited to the surface. Furthermore, for thick ($\geq$1.5 mm) PLA samples, degradation has been shown to proceed by means of a heterogeneous mechanism.[39–44] As a result, the interior of the material degrades faster than the surface due to autocatalysis from the carboxylic acid end groups of the degrading products that cannot easily diffuse out of the material.

In previous work,[45] telechelic acrylic PLA oligomers were synthesized, formulated with different reactive diluents, and photopolymerized into films in order to investigate the influence of PLA concentration and choice of reactive diluent on the mechanical properties. It was found that as the PLA concentration increased, the conversion and crosslink density of the films decreased resulting in softer more flexible films. Furthermore, films were formulated to contain either 1,4-butanediol dimethacrylate (BDDM) or triethylene glycol dimethacrylate (TEGDMA). Films containing TEGDMA had a slightly lower crosslink density and conversion resulting is films that were more flexible than films contacting BDDM for a given PLA concentration. In this article, the photopolymerizable film formulations studied in earlier work[45] were employed to investigate the use of formulation as a fast and easy method to change the hydrophilicity and enzymatic degradation of photopolymerized films containing PLA. Hydrophilicity of the films was investigated by determining the amount of water uptake as a function of submersion time in water. Enzymatic degradation of the films was investigated using proteinase K, *Chromobacterium viscosum* (CvL), *Rhizomucor miehei* (RmL), or *Candida cylindracea* (CcL). Ester hydrolysis was evaluated using titration and MS. The aim of this article is to introduce a simple method to vary the structure of biocompatible PLA films by using a reactive diluent approach.

EXPERIMENTAL

Materials

All materials were used without further purification. For the production of films, DL-lactic acid 85%, ethylene glycol diacrylate 90% (EGDA), neopentyl glycol diacrylate 95% (NPGD), trimethylolpropane triacrylate 95% (TMPTA), BDDM 95%,

Table I. Weight Percentage of Materials Used in Each Sample Formulation

Sample	Telechelic acrylic PLA (wt %)	NPGD (wt %)	TMPTA (wt %)	BDDM (wt %)	TEGDMA (wt %)
BDDM0PLA	0	10	36	50	0
BDDM10PLA	10	10	36	40	0
BDDM30PLA	30	10	30	26	0
BDDM50PLA	50	10	25	11	0
BDDM70PLA	70	3	20	3	0
TEGDMA0PLA	0	10	36	0	50
TEGDMA10PLA	10	10	36	0	40
TEGDMA30PLA	30	10	30	0	26
TEGDMA50PLA	50	10	25	0	11
TEGDMA70PLA	70	3	20	0	3

TEGDMA 95%, titanium isopropoxide 97% (TIP), dibutyltin(IV) oxide 98% (DBTO), silica gel (70–230 Mesh ASTM), hexane (99%), ethyl acetate (99%), ammonia hydroxide solution (28.0–30.0% NH_3 basis), sodium hydroxide, and sodium chloride were purchased from Aldrich. Irgacure 2959 was obtained from Ciba Specialty Chemicals. Aluminum mill finish 2024-T3 (3×6 in^2) panels were obtained from Q-Panel Lab Products.

For degradation studies, proteinase K from *T. album*, lipase from *C. viscosum* (CvL), and lipase from *R. miehei* (RmL) were purchased from Aldrich. Lipase from *C. cylindracea* (CcL) was purchased from Fluka.

Synthesis of Telechelic Acrylic Poly(lactic acid)

Telechelic acrylic PLA oligomers were synthesized according to pervious work by Miller and Soucek.[45] A clear viscous solution was obtained with a product yield of 77%. M_n from gel permeation chromatography (GPC): 1713 with polydispersity index (PDI) 1.8; M_n from ^{1}H-NMR end group analysis: 2079. ^{1}H-NMR ($CDCl_3$) δ (ppm) 1.55 (*d*, —CH_3), 5.15 (m, —CH—), and 5.8–6.4 (acrylic end groups CH=CH_2). ^{13}C-NMR ($CDCl_3$) δ (ppm); 17.01 (—O—CH(CH_3) —CO), 69.37 (—O—CH(CH_3) —CO), 169.95 (—O—CH(CH_3) —CO), 132.57 (CH_2=CH—CO), 129.03 (CH_2=CH—CO), and 62.07 (—O—CH_2—CH_2—O—). Mass spec peaks observed at $m/z = 1287$, 1215, 1143, 1071, etc. (m/z clusters decrease by 72, PLA repeat unit).

Formulation and Preparation

Telechelic acrylic PLA oligomers were formulated with different reactive diluents and cured according to pervious work by Miller and Soucek.[45] Table I shows the sample formulations.

Characterization

The ^{1}H- and ^{13}C-NMR spectra of PLA and acrylate terminated PLA were recorded in a Varian Mercury 300MHz spectrophotometer. All the NMR spectra were measured by dissolving the samples in $CDCl_3$.

Molecular weight and molecular weight distribution of PLA and telechelic acrylic PLA was determined with a Waters GPC instrument equipped with Waters HR4 and HR2 styragel columns, a Waters differential refractometer and a Viscotek 760A dual light scattering and viscosity detector. Samples were dissolved in THF and the flow rate was 1 mL min^{-1}. Poly(styrene) was used as the calibration standard.

Water Uptake

Water uptake of films was determined by taking a 10 mm × 30 mm × 127 μm film and drying it in a vacuum oven until the weight change was stabilized. Next the film was placed in 20 mL of deionized water. After soaking for the desired amount of time, the film was removed from the water, blotted on filter paper to remove any excess surface water, and weighed. The amount of water uptake was calculated according to eq. (1),

$$\text{Water uptake} = \frac{W_{\text{after}} - W_{\text{before}}}{W_{\text{before}}} \times 100\% \quad (1)$$

where W_{after} is the weight of the sample after water absorption and W_{before} is the sample weight before immersion in water.

Enzymatic Ester Cleavage

The biocatalytic ester cleavage of the films was monitored by measuring the amount of acid released via titration. Film strips (10 mm × 30 mm × 127 μm) were placed in a 20 mL glass vial. Next, a 0.9% NaCl solution was added to the vial and the pH was adjusted to 7 through the addition of sodium hydroxide. The amount of NaCl solution was enough so that upon addition of the enzyme, the final solution volume would be 6 mL and the enzyme concentration would be 30 U/mL. Reaction was started by adding the enzyme and the ester hydrolysis was monitored by recording the amount of 0.01*M* sodium hydroxide solution required to keep a constant pH of 7. The pH was monitored by using an Oakton pH 11 series meter. The degradation rates (μmol/min) of the films were calculated from the initial slope of the ester cleavage versus degradation time curves.[46]

After immersion of the sample for 200 min in a degradative enzyme solution, a fraction of the sol was removed and evaluated by mass spectrometry. Matrix assisted laser desorption ionization- mass spectroscopy (MALDI-MS) and MS/MS experiments were performed on a Waters Q/Time of flight (TOF) Ultima quadrupole/orthogonal-acceleration time-of-flight mass spectrometer (Milford, MA), equipped with a pulsed nitrogen laser emitting at 337 nm. Solutions of dithranol matrix (20 mg/mL), degraded polymer solution (10 mg/mL), and lithium trifluoroacetate cationizing agent (10 mg/mL) were mixed in the ratio 10 : 2 : 1, and ~1.0 μL of the final mixture was deposited on the 96-well sample holder plate that is inserted into the MALDI source. The ions exiting the MALDI source were directed toward the quadrupole mass filter, which was set to transmit one oligomer mass only (mass-selective mode) for the MS/MS experiments. The precursor ion resolution can be adjusted to select one isotope or the complete isotopic cluster of an oligomer. The selected ion proceeded to an rf-only hexapole collision cell, pressurized with Ar at ~0.9−1.0 bar, where collision activated dissociation (CAD) took place at laboratory-frame kinetic energies that can be varied up to 200 eV (multiple collision conditions). The fragment and undissociated precursor ions exiting the collision cell were focused through an rf-only hexapole lens, and the focused ion packet was accelerated orthogonally by ~10 kV into the TOF region for mass analysis. Control mass spectra were measured with the TOF mass analyzer by setting the quadrupole mass filter to rf-only mode, so

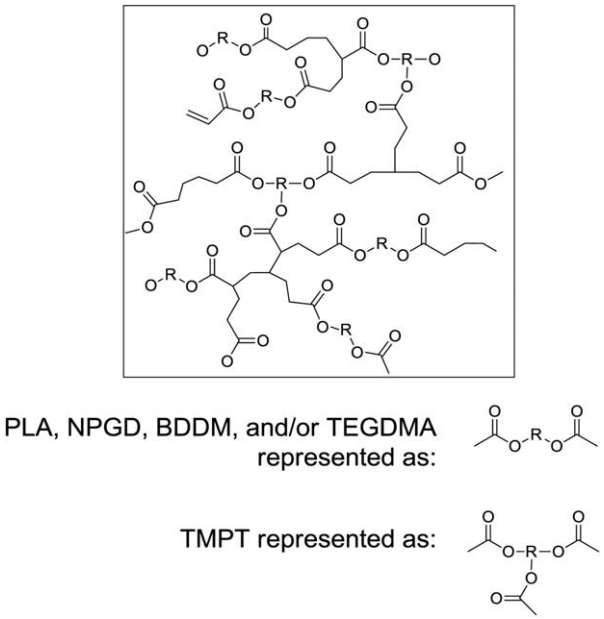

Figure 1. Depiction of crosslinked network formed after photopolymerization.

that it transmitted all ions produced in the MALDI source. The ion abundances of several TOF MS or MS/MS scans were summed to obtain spectra with good signal-to-noise ratio. The quoted *m*/*z* values are monoisotopic.

Delamination of Photopolymerized Film

The time required for delamination of films was investigated by spraying a solution onto the film surface and monitoring the time required until the film released from the surface and could be wiped off. Films photopolymerized on aluminum panels were sprayed with an enzyme solution or a 5% (wt/wt) ammonia solution (2.9*M*). Enzyme solution consisted of a 0.9% NaCl solution with an enzyme concentration of 30 U/mL. The time required for the films to delaminate off the panel and be wiped off was recorded. Films were sprayed every 30–60 min with the correct solution to ensure the film surface remained wet.

RESULTS

Telechelic acrylic PLA oligomers were formulated with reactive diluents and photopolymerized into films. A depiction of the photo-crosslinked network is shown in Figure 1. Since the PLA oligomers were modified with acrylic groups, the copolymer composition could be changed by choice of reactive diluent and, of course, percentage of reactive PLA oligomer. It is anticipated that changing the film hydrophilicity will lead to different enzymatic degradation rates, as such, films containing different concentrations of telechelic acrylic PLA and either BDDM or TEGDMA were prepared in order to alter the film properties without additional synthetic work of deriving thermoplastic polymers. Formulation with BDDM or TEGDMA was chosen to control the hydrophilicity of the samples; TEGDMA introduces poly(ethylene glycol) segments that have good water solubility,[47] while BDDM does not. All the monomers were chosen such that each contained at least one hydrolytically cleavable bond and were shown to be biocompatible.[48,49] Photoinitiator Irgacure 2959 was chosen due to its low toxicity.[50]

Water Uptake of Films

The hydrophilicity of each film was investigated by measuring the water uptake of the films. The water uptake for each of the films as a function of time is shown in Figure 2. For each set of formulations, as the concentration of PLA increases so does the water uptake. BDDM formulations showed a fivefold increase in water uptake when PLA concentration increased from 0 to 70 wt % PLA. Likewise, TEGDMA formulations showed a fivefold increase in water uptake for the same increase in PLA concentration. The difference between the BDDM and TEGDMA samples was that the BDDM sample series started a 10 wt % water uptake (BDDM0PLA) while the TEGDMA samples started at 19.4 wt % water uptake (TEGDMA0PLA).

Degradation Kinetics

Although proteinase K has been shown to be an excellent enzyme to degrade PLA, many of these films contain less than 50 wt % PLA. As such, three additional enzymes (CvL, RmL, and CcL) were used for the enzymatic degradation of the

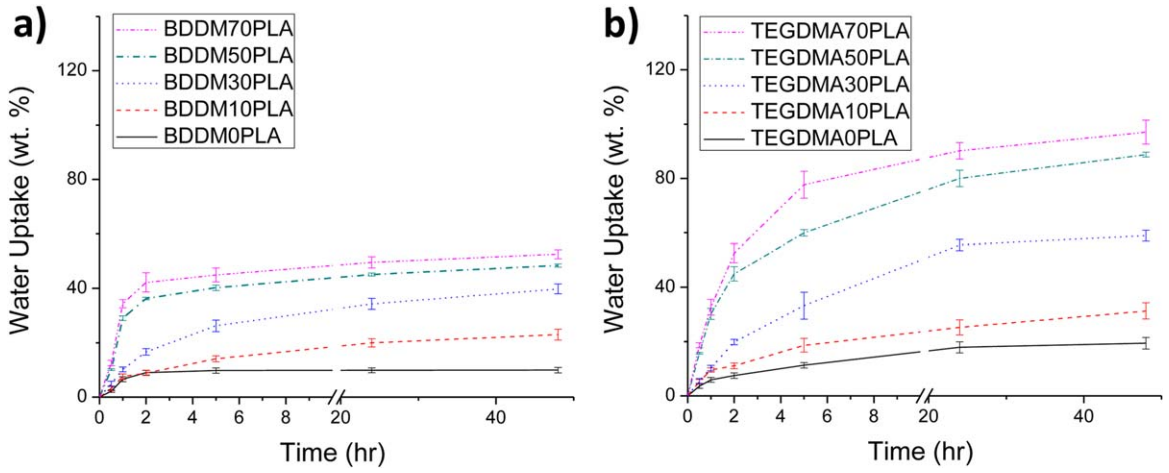

Figure 2. Water uptake as a function of submersion time for (a) BDDM films and (b) TEGDMA films. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

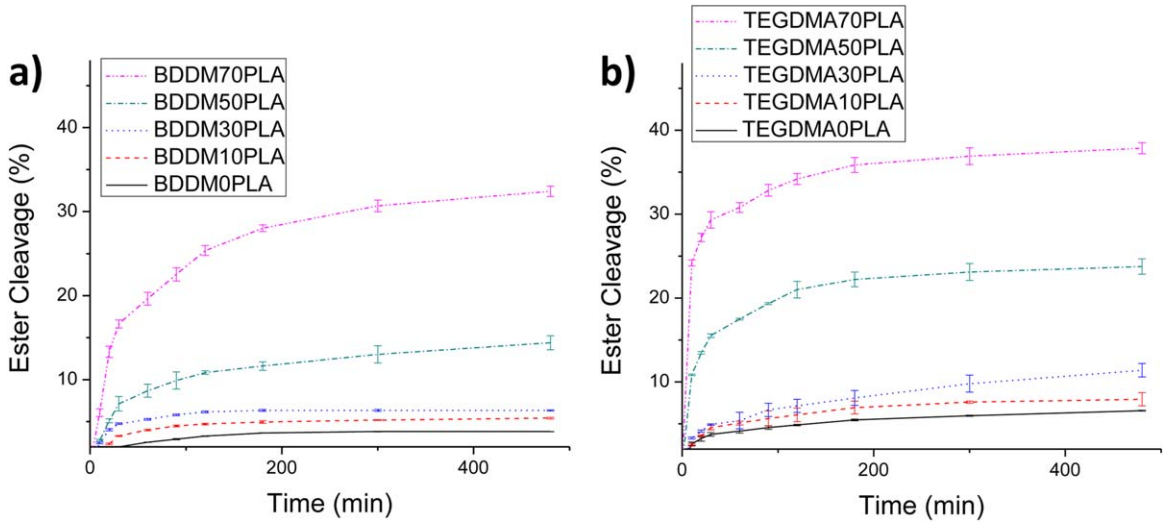

Figure 3. Ester cleavage by proteinase K as a function of time for (a) BDDM films and (b) TEGDMA films. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

photopolymerized films. The enzymatic degradation of each sample was studied by monitoring the amount of ester cleavage that occurs. Figures 3–6 show the ester cleavage of each sample as a function of time for a 30 U/mL enzyme solution of proteinase K, CvL, RmL, or CcL. For each formulation series, BDDM or TEGDMA, a marked increase in enzymatic degradation is observe as the PLA concentration increases for 0–70 wt % for all enzyme solutions. Furthermore, for a given PLA concentration, samples formulated with TEGDMA showed a greater amount of ester cleavage than those samples containing BDDM.

The greatest amount of ester cleavage was obtained with proteinase K. The ester cleavage obtained by the other enzymes decreased in the following order: CvL > RmL > CcL. For the BDDM formulation series, BDDM70PLA had the greatest amount of degradation with the following ester cleavage amounts after 480 min: 31.4, 22.7, 12.9, and 6.0% corresponding to the enzymes proteinase K, CvL, RmL, and CcL respectively. While TEGDMA70PLA had the greatest amount of degradation for the TEGDMA formulation series, 36.8, 26.0, 14.5, and 8.2 % ester cleavage after 480 min corresponding to the enzymes proteinase K, CvL, RmL, and CcL respectively.

The degradation rates of the BDDM and TEGDMA sample sets as a function of PLA concentration are shown in Figure 7. It is observed that as the PLA concentration increases, the degradation rate also increases. Furthermore, for a given PLA concentration, degradation rates for the different enzyme solutions followed the same order as those that gave the highest ester cleavage amount: Proteinase K > CvL > RmL > CcL. For sample BDDM70PLA, Proteinase K produced the highest degradation rate of 0.0035 μmol/min, which was 2.5-fold higher than degradation by CvL, 3-fold higher than RmL, and 4-fold higher than CcL. TEGDMA samples showed a similar trend, but

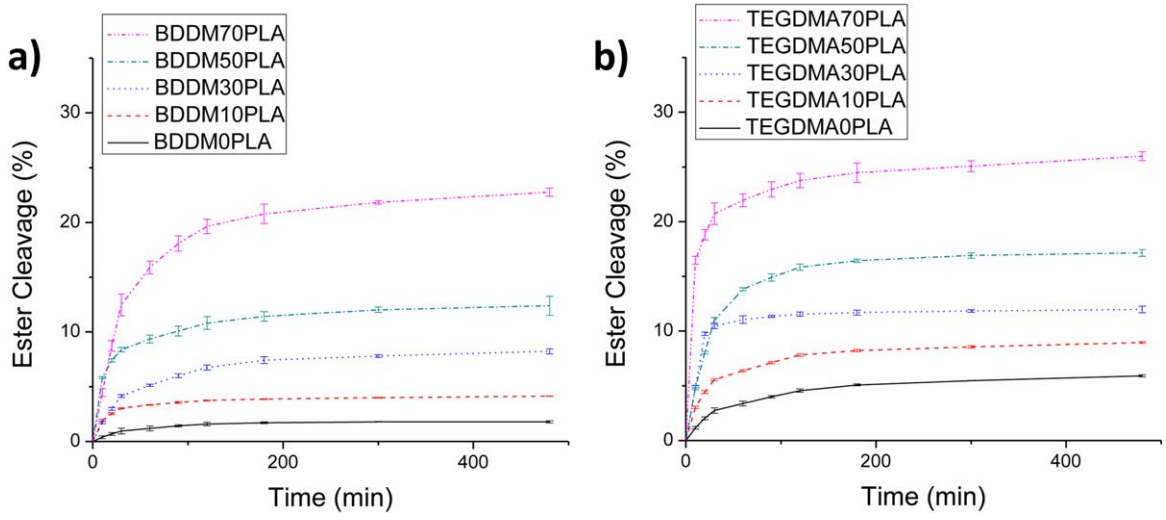

Figure 4. Ester cleavage by CvL as a function of time for (a) BDDM films and (b) TEGDMA films. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

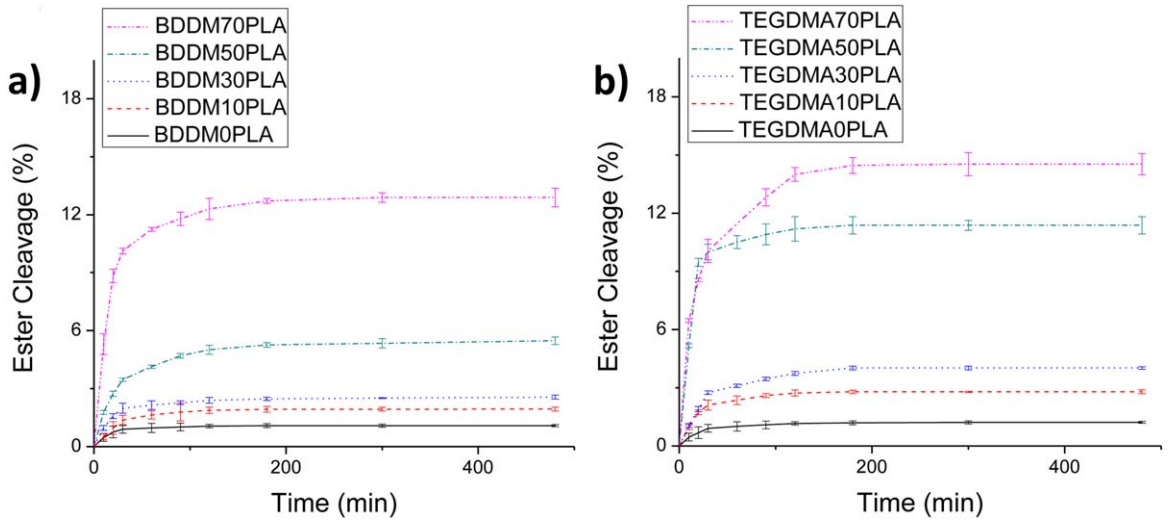

Figure 5. Ester cleavage by RmL as a function of time for (a) BDDM films and (b) TEGDMA films. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

degradation rates were higher than those of BDDM. For sample TEGDMA70PLA, proteinase K solution gave a degradation rate of 0.0057 μmol/min which was 2.1, 3.8, and 5.2-fold higher than degradation by CvL, RmL, and CcL, respectively. Similar trends were observed in all other film samples.

The MS and MS/MS analysis of the sol showed that the fragmentation products display a structural unit difference of 72, lactic acid,[51] which is the same m/z difference that both the synthesized PLA and telechelic acrylic PLA oligomers displayed. Figure 8 shows the MS and MS/MS spectra for sample TEGDMA70PLA. All other spectrum for samples containing PLA showed similar results, a structural repeat unit of 72 was observed. As for the degradation of the films without any PLA (BDDM0PLA and TEGDMA0PLA), the signal from the degradative byproducts were too weak to detect. This indicates that the vast majority of the degradation byproducts are from the degradation of PLA. This does not mean that no reactive diluents are being degraded, just that at the degradative time scale that is being investigated, PLA is degraded at a much more appreciable rate than the other reactive diluents.

Degradation Assessment of Film

The enzyme solutions used in the ester cleavage tests were also used to investigate the time it would take, if possible, to remove the photopolymerized films from the substrate. In addition to the enzyme solutions, a 5% (wt/wt) ammonia solution was also used to remove films to compare biocatalyzed degradation to that of an alkaline environment. Time required to remove the film is shown in Table II. It is desirable to be able to degrade short-term/disposable materials in a timely manner; therefore, removal of films by means of applied solution was only monitored for 24 h. For a given degradative solution, the removal time of the film from the substrate was inversely proportional to the concentration of PLA in the system. Formulations with TEGDMA showed a faster time to delaminate than those of

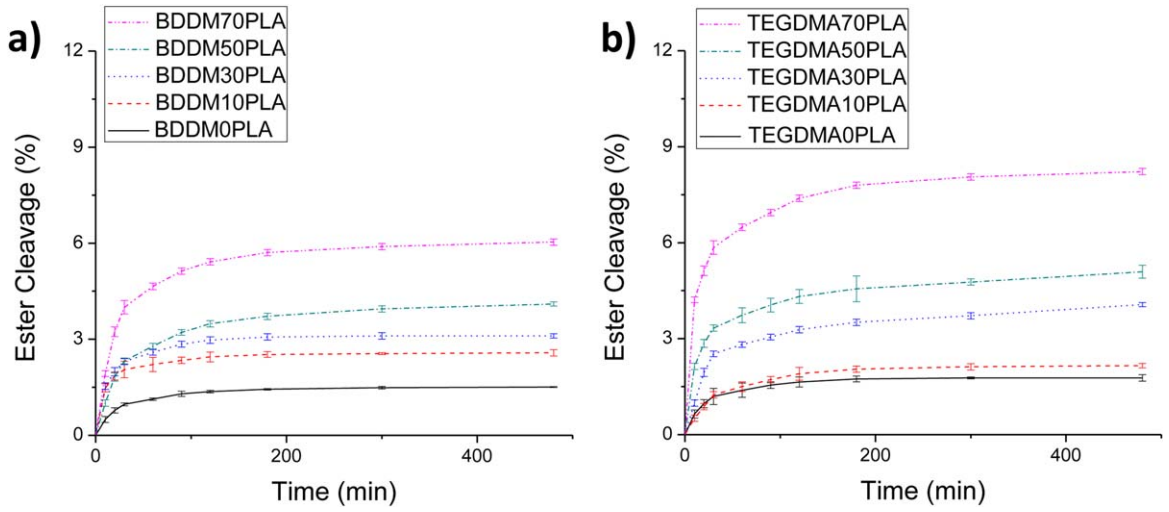

Figure 6. Ester cleavage by CcL as a function of time for (a) BDDM films and (b) TEGDMA films. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

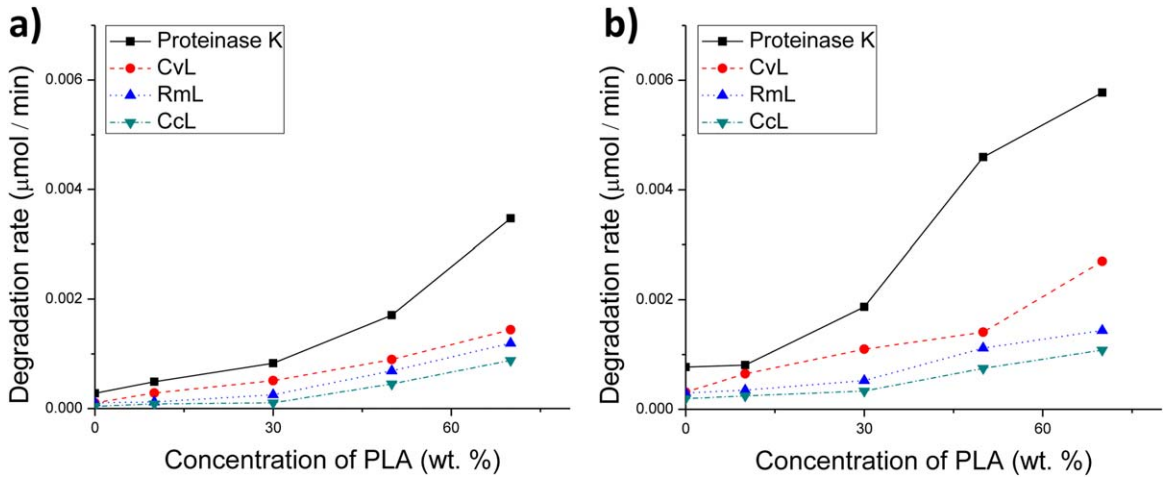

Figure 7. Degradation rate as a function of PLA concentration for different enzyme solutions for (a) BDDM films and (b) TEGDMA films. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

BDDM. Neither the BDDM0PLA nor TEGDMA70PLA showed any signs of delamination due to low water uptake. Low water uptake means that the enzyme solution cannot easily diffuse into the film. As a result, degradation most likely occurs on the surface and as such the film will not begin to degrade near the substrate surface for quite some time, causing delamination to occur very slowly.

It has been observed that alkaline conditions result in much faster and higher amounts of degradation than those obtained through enzymatic degradation.[24,52–54] Therefore, it is desirable to know how much faster an alkaline solution can remove the films over that of an enzyme solution. Although an alkaline solution is not as environmentally friendly as an enzyme solution, applications that require fast removal of a film could benefit from the use of an alkaline solution. An acidic environment was not tested because it has been shown that alkaline environments have a much larger impact on degradation.[55–57] For both sample sets, BDDM and TEGDMA, delamination occurred the fastest when the films were exposed to ammonia solution. As for the enzyme solutions, proteinase K had the fastest removal time followed by CvL, RmL, and CcL. Ordering of the enzyme solutions is as expected, same order was found in the ester cleavage amount and degradation rates.

DISCUSSION

The ability to change the hydrophilicity and degradation properties of films containing PLA has been investigated by multiple researchers via the production of various block copolymers.[25,27–38] While these techniques allow film properties to be controlled, it is a time consuming processes that requires additional synthesis, purification, and optimization of reaction conditions. Formulation with reactive diluents is a faster and more simple approach compared to the synthesis of various new copolymers which is the approach undertaken by all the other researchers thusfar.[25,27–38]

Enzymatic degradation of the formulated PLA films was investigated by means of titration. The use of titration is a convenient method to determine the amount of degradation a sample has undergone because it is a direct measure of the acid groups formed upon hydrolysis of the ester bonds. From the titration

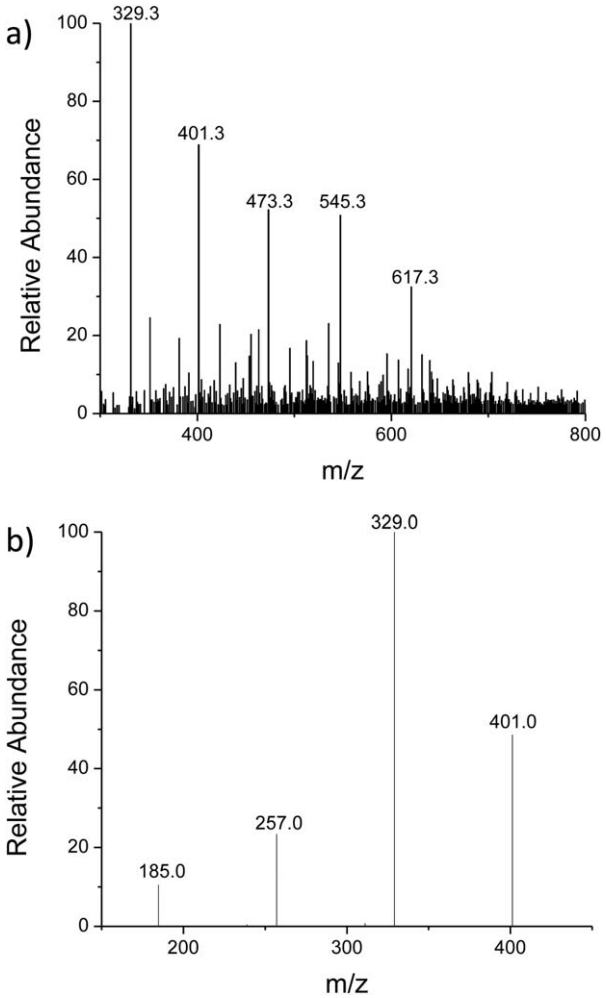

Figure 8. (a) Mass spectra of sol fraction from the degradation of sample TEGDMA70PLA by proteinase K and (b) MS/MS spectra of *m/z* 401.3 in (a).

Table II. Time Required for Delamination of Coating (min)

	Agent for degradation				
Sample	Proteinase K	CvL	RmL	CcL	Ammonia
BDDM0PLA	X[a]	X	X	X	X
BDDM10PLA	> 1440[b]	X	X	X	1200
BDDM30PLA	1140	1260	> 1440	>1440	780
BDDM50PLA	320	450	720	1380	230
BDDM70PLA	80	120	290	900	35
TEGDMA0PLA	X	X	X	X	X
TEGDMA10PLA	1080	1320	1425	>1440	900
TEGDMA30PLA	480	1008	1170	1400	300
TEGDMA50PLA	150	180	300	580	100
TEGDMA70PLA	30	50	135	330	19

[a] X means that after 1440 min coating did not show any signs of delamination.
[b] >1440 means that coating was in initial stages of delamination.

experiments, the amount of ester bond cleavage that each sample underwent as a function of time in various enzyme solutions was determined. It was observed that samples with higher PLA concentrations as well as those formulated with TEGDMA had a higher ester bond cleavage amount for a given enzyme solution as well as a higher degradation rate. The variation in the degradation of each sample can be related to the water uptake. As observed in Figure 2, as the PLA concentration in each sample increases the amount of water uptake increases. The rise in water uptake is due to the increase in free volume within the film as a result of decreasing crosslink[45]density due to an increase in long chain PLA oligomer content. Furthermore, for a given PLA concentration samples formulated with TEGDMA showed a greater water uptake than those formulated with BDDM. TEGDMA films have greater water uptake because the addition of poly(ethylene glycol) enhances the hydrophilicity of the film.[25,28,36,47]

Degradation is faster for the samples with greater water uptake because the faster the enzyme solution can enter the interior of the film the faster it can begin to catalyze hydrolysis of the material, resulting in a more readily degradable material.[58] Additionally, as the swelling of the film increases, the mobility of the polymer chains become greater. Chain mobility is very important because the chains must be able to reach and conform to the active sites of the enzyme before the enzyme can begin to catalyze ester cleavage.[59,60] Chain mobility was also enhanced for films containing greater amounts of PLA due to a decrease in crosslink density, as determined in previous work.[45] As the crosslink density decreases, free volume increases which allows for greater chain mobility. Films with higher concentrations of PLA have a much greater water uptake and lower crosslink density; therefore, the PLA chains are much more mobile and can more easily interact with the enzymes, leading to faster ester hydrolysis. The fact that degradation is mainly confined to PLA is further confirmed from the MS and MS/MS spectra, a structural repeat unit of 72 is observed for all sol fractions of the enzyme degraded samples containing PLA. Since the enzyme solution can more easily enter into the PLA rich areas of the film, degradation occurs more readily in these areas. As degradation proceeds, the degraded byproducts of the PLA region diffuse out of the film and into the sol. Degradation of the acrylic rich phases will occur in time.[48] However, due to the fact that the water uptake is much slower in the acrylic rich areas, these materials require a longer time scale to show appreciable degradation byproducts. An exaggerated depiction of enzymatic degradation for the PLA film is shown in Figure 9.

To more easily discern how water uptake affects the degradation rate, regardless of the sample formulation, a plot of degradation rate as a function of water uptake is shown in Figure 10 for each enzyme. Since degradation rates are from the initial slope of the ester hydrolysis curves, water uptake at approximately 30 min should be considered for this comparison. Based on Figure 10, samples can be placed in the following order, from highest degradation rate and water uptake to the lowest; TEGDMA70PLA < TEGDMA50PLA < BDDM70PLA < BDDM50PLA < TEGDMA30PLA < TEGDMA10PLA < BDDM30PLA < TEGDMA0PLA < BDDM10PLA < BDDM0PLA. A linear regression was fit to the data points for each enzyme with an intercept at the origin; slope and correlation coefficient values are given in Table III. Although other researchers have investigated the relationship between water uptake and enzyme degradation for PLA films,[17,25,26,39,61,62] this is a first time the two properties have been directly correlated for photopolymerizable PLA films. Correlating these two properties is important, because, when coupled with the process of formulation, one can easily design and produce PLA films that contain the required degradation kinetics by altering the formulation to meet a specific hydrophilicity, and therefore degradation rate.

Not only does water uptake play an important role in the degradation of the films, but the degradative environment (enzyme solution) also impacts the degradation of the films. It was observed that films immersed in a proteinase K solution gave the greatest degradation rate and ester cleavage amount. CvL solutions gave the second highest rates and degradative cleavage amounts followed by RmL and CcL solutions. Even though, for a given sample, the water uptake is the same, in order to have effective

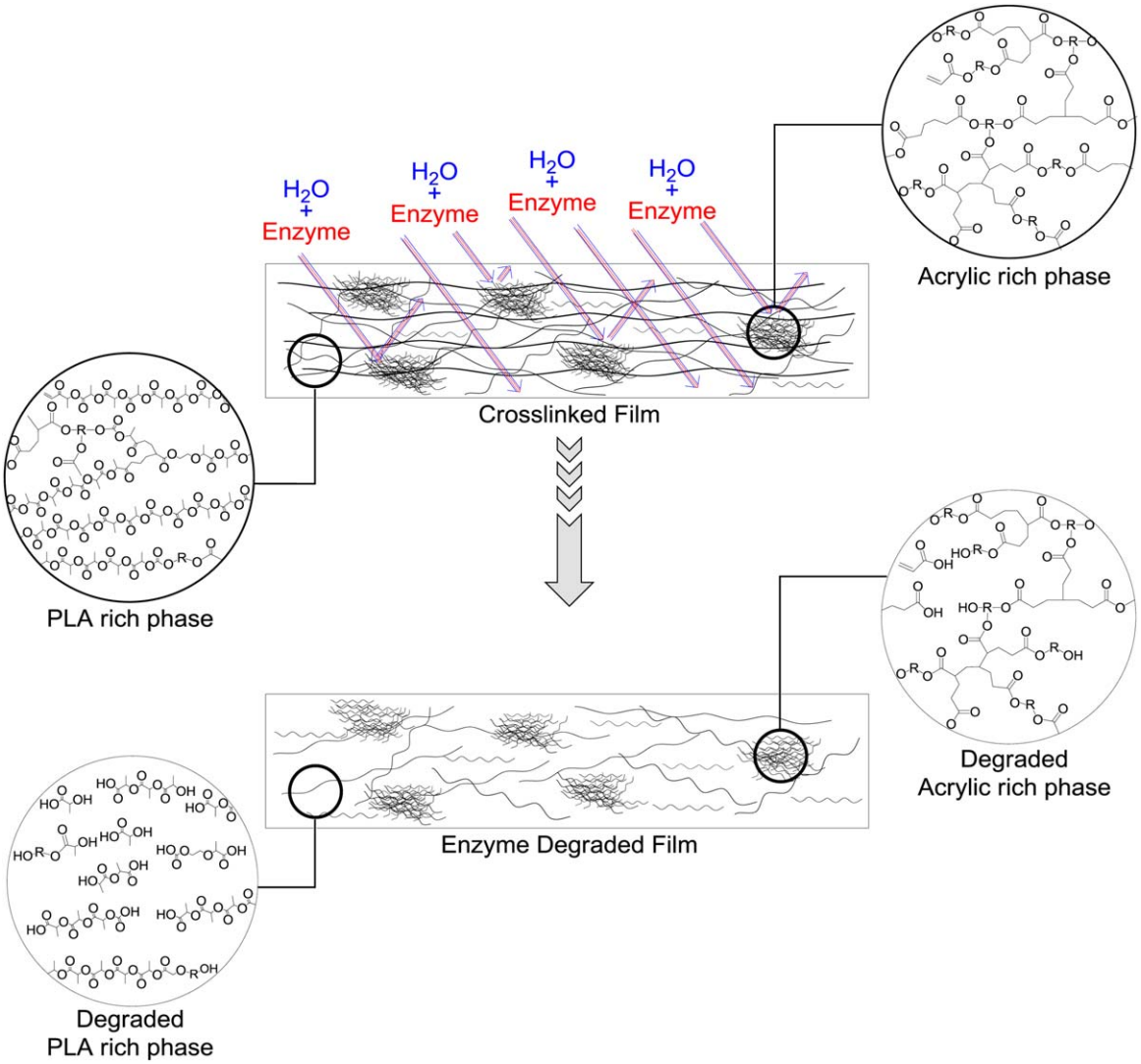

Figure 9. Depiction of enzymatic degradation of PLA film. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

biocatalyzed ester hydrolysis the enzyme needs to be able to quickly complex with the substrate, hydrolyze the ester bonds, and release the product. However, the activity of each enzyme toward ester hydrolysis is greatly dependent on the chemical structure and molecular environment in which the ester bonds are contained.[46] The fact that Proteinase K was the best enzyme, highest amount of degradation, was expected because Proteinase K is known to be an excellent enzyme for the degradation of PLA.[16–19]

Biodegradable films with controllable properties can easily be produced by means of fast and easy formulation changes. Formulation permits very small changes to be made rapidly and efficiently, thus, one can obtain the desired film properties much faster than through conventional synthetic methods. Additionally, formulation by-passes any synthetic limitations, such as purification and/or precise control over monomer content in the co-polymer, giving greater control over the hydrophilicity and degradation rates of the film.

The use of formulation to produce biocompatible/biodegradable materials can have a tremendous impact on drug delivery systems,[8–10,63–65] implantable devices,[66,67] and tissue engineering.[1,3,4] Due to the fact that formulation offers a faster and easier way to produce biomaterials with specific properties, medical devices can more readily be tailored to meet each patient's specific needs. For example, controlled release drug delivery systems can be formulated and produced relatively easy to ensure that a patient gets the required amount of medication at the right time, as opposed to relying on large scale drug

Table III. Scaling Factor and Correlation Coefficient Values Obtained by Linear Regression ($y = kx$) of the Degradation Rate vs. Water Uptake Data in Figure 10

Enzyme	k	R
Proteinase K	2.72×10^{-4}	0.959
CvL	1.16×10^{-4}	0.951
RmL	7.62×10^{-5}	0.979
Ccl	5.44×10^{-5}	0.976

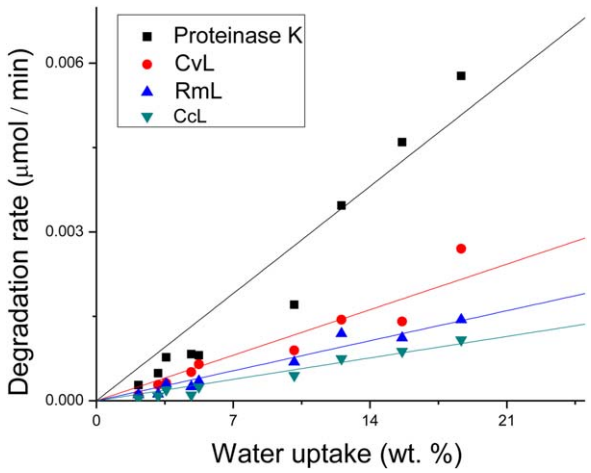

Figure 10. Degradation rate as a function of water uptake (after 30 min) for films in different enzyme solutions with fitted linear regression line ($y = kx$). The calculated scaling factor (k) and correlation coefficient are shown in Table III. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

production for a generalized audience. This customized approach to drug delivery systems, and in fact any biomedical device, will be highly beneficial.

CONCLUSIONS

Telechelic acrylic PLA oligomers were synthesized and formulated with reactive diluents, then photopolymerized into a biodegradable film. The concentration of PLA in a film had a dramatic impact on the amount of water uptake and enzymatic degradation. Higher concentrations of PLA resulted in films with higher water uptake and enzymatic degradation. Likewise, films formulated with TEGDMA showed a greater amount of water uptake and enzymatic degradation as opposed to those formulated with BDDM. Water uptake plays a crucial role in degradation because the more an enzyme solution can enter into a film the greater the amount of degradation and higher the degradation rate. This is impart due to the fact that as a film swells the mobility of the chains increases which allows them to more easily conform to the active sites of the enzyme.[59,60] The amount of ester cleavage was the most pronounced upon submersion of the films in a Proteinase K solution. This is especially true for those samples that contain large concentrations of PLA. It was also found that alkaline hydrolysis was much faster than that of biocatalyzed ester hydrolysis as determined by delamination tests. The properties including water uptake, enzymatic degradation, and delamination time could be easily controlled by changing the type and concentration of reactive diluent.

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