

# Modification of PLA Derivative Using Low Energy Electron Beam (EB) Irradiation

Peikai Miao, Wenrui Tang, Ke Zeng, Yan Tang, Gang Yang\*

*Application and Research Center for Electron Beams of College of Polymer-NHVC,  
Department of Polymer Science & Engineering, State Key Laboratory of Polymeric Materials  
Engineering, Sichuan University, Chengdu 610065, China*

## ABSTRACT

Poly(D,L-lactic acid)-co-poly(ethylene glycol) copolymer (D,L-PLEG) synthesized by melt polycondensation was irradiated using low energy electron beam (EB) in the presence of triallyl cyanurate (TAC) and tetraallyl pentaerythritol (TAPE) as crosslinking agents. The tensile strength of D,L-PLEG/TAC and D,L-PLEG/TAPE samples increased up to 48 MPa and 28 MPa at dose of 80 kGy and 60 kGy, respectively, and decreased with further increase of dose, while the elongation at break decreased continuously with increasing dose. DSC analysis showed that the heat stability of crosslinked D,L-PLEG was improved to some extent because of wide formation of molecular chain network. Degradation of D,L-PLEG was retarded with introduction of crosslinking network. The results suggest that the crosslinked D,L-PLEG has great potential for applications in industrial and biomedical fields.

**Keywords:** D,L-PLEG; polyfunctional monomer; radiation-induced crosslinking; low energy electron beam

## 1. Introduction

Poly(lactic acid)-co-poly(ethylene glycol) (PLEG), synthesized by ring-opening polymerization of L(D)-lactide in the presence of poly(ethylene glycol) (PEG)<sup>1</sup>, has the suitable combination of properties for use as drug delivery matrix<sup>2,3</sup>. The process, however, requires very high purity lactide and is economical only for high priced medical and pharmaceutical applications. And the tensile strength and heat resistance of PLEG are poor because of the presence of POE flexible chain. Meanwhile, it is difficult to synthesize PLEG with high molecular weight. To improve these properties and extend its application fields, it is a powerful method to introduce crosslinking between polymer molecules. There are some reports about the PLEG derivative crosslinked by photopolymerization in the presence of photoinitiator<sup>4,5</sup>.

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\* Corresponding author. Tel: 86-28-85469766; fax: 86-28-85469766.

*E-mail address:* yanggang65420@163.com (G. Yang).

Electron beam (EB) irradiation has been well known as a very convenient, efficient and photoinitiator-free tool for modification of polymers through crosslinking, grafting and degradation techniques. When the polymer is exposed to an EB, its mechanical and physical properties decrease due to reduction of the molecular weight of the polymer<sup>6</sup>. There are recent reports concerning improvement of mechanical properties and heat stability by employing polyfunctional monomers (PFM) as crosslinking agents to introduce crosslinking of some biodegradable polymers during irradiation<sup>7,8</sup>.

Therefore, crosslinking technology could be an effective method for the modification of D,L-PLEG by EB irradiation. In this work, D,L-PLEG was synthesized by melt polycondensation, using low-cost D,L-lactic acid and PEG as raw materials. Two kinds of PFM, Triallyl cyanurate (TAC) and tetraallyl pentaerythritol (TAPE) as shown in Fig. 1, were chosen as crosslinking agents. The effects of low energy EB radiation on the degradability, mechanical, thermal properties of D,L-PLEG/PFM composite were investigated. It was expected that the introduction of crosslinking would not only overcome the low tensile and thermal properties of D,L-PLEG, but also extend the application fields of this material as a novel degradable plastic which can be used in industrial and biomedical fields.

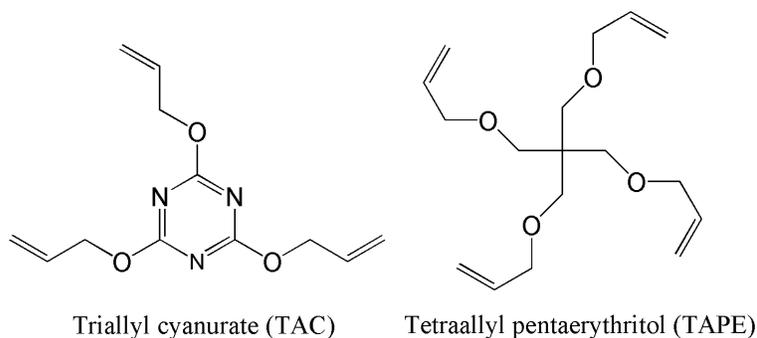


Fig. 1. The structure of polyfunctional monomers (PFM) as crosslinking agents.

## 2. Experimental

### 2.1. Materials

D,L-lactic acid (85-90 wt.% aqueous solution) and poly(ethylene glycol) (PEG) with weight average molecular weights of 6000 (PEG 6K) were purchased from Tianjin Bodi Chemical Co., Ltd. (China). Tin(II) chloride dihydrate ( $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ ) was purchased from Chongqing Chemical Reagent Company (China). p-toluenesulfonic acid (TSA) was purchased from Chengdu Kelong Chemical Reagent Company (China). Acetone, dichloromethane (DMC), and methanol were laboratory reagents. Triallyl cyanurate (TAC) and tetraallyl pentaerythritol (TAPE) were synthesized according to the literatures<sup>9,10</sup>. All Chemicals were analytical grade and used without further purification.

## 2.2. Synthesis of Poly(D,L-lactic acid)-co-poly(ethylene glycol) Copolymer (D,L-PLEG)

The synthesis of a copolymer of D,L-lactic acid with PEG 6K, carried out by a modification of existing literature techniques and procedure<sup>11,12</sup>.

A total of 100 g of D,L-lactic acid (85-90 wt.%) was dehydrated at 100 °C, first at atmospheric pressure for 1 h, then at a reduced pressure of 20 torr for 1 h, and finally under a pressure of 5 torr for another 4 h at 150 °C. Then, a viscous liquid of oligo(D,L-lactic acid) (ODLLA) was formed quantitatively.

A 200 mL pyriform three-necked flask was equipped with a mechanical stirrer and a reflux condenser that was connected with a vacuum system through a cold trap. A total of 40 g of ODLLA, 3.60 g of PEG 6K, 0.16 g of SnCl<sub>2</sub>·2H<sub>2</sub>O (0.4 wt.% relative to ODLLA), and 0.12 g of TSA (an equimolar ratio to SnCl<sub>2</sub>·2H<sub>2</sub>O) were charged into the flask. The reaction mixture was stirred under a pressure of 5 torr at 180 °C for 18 h and was subsequently cooled to room temperature. The resulting copolymer was dissolved in acetone, precipitated in the mixture of methanol and distilled water (v/v=1:6), filtered, and dried under vacuum (yield 72 %).

## 2.3. Preparation of Samples and Irradiations

D,L-PLEG and polyfunctional monomer (PFM) were dissolved in DCM completely. The content of D,L-PLEG was 40 wt.%, and the dosage of PFM was 3 wt.% relative to D,L-PLEG. Then, the sample was treated to form the film with thickness of 24 μm by spin-coating method. Finally, the film was dried in a vacuum oven at 40 °C for 36 h. For comparison, D,L-PLEG without any PFM was treated with the same procedure.

The film sample was irradiated by low energy electron beam (NHV Corporation, Japan. Accelerating voltage: 150 kV, beam current: 5 mA, dose rate: 20 kGy pass<sup>-1</sup>) at nitrogen atmosphere with the content of oxygen of less than 100 mg L<sup>-1</sup> (Fig. 2).

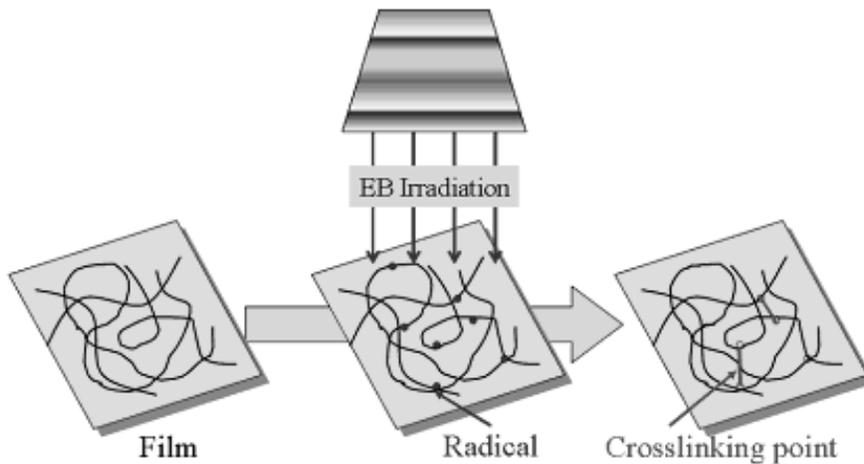


Fig. 2. Schematic illustration of the radiation-induced crosslinking modification process for D,L-PLEG copolymer

## 2.4. Measurements

### 2.4.1. Gel fraction and water uptake of irradiated samples

Gel fraction of the irradiated samples was estimated by measuring its insoluble part in dried sample after immersion in DCM for 48 h at room temperature. The gel fraction was calculated according to the following equation:

$$\text{Gel fraction (\%)} = (G_d/G_i) \times 100 \quad (1)$$

where  $G_i$  is the initial mass of the dried sample after irradiation and  $G_d$  is the mass of dried insoluble part of sample after extraction with DCM.

### 2.4.2. Tensile properties measurement

Tensile tests were carried out according to ISO 1184 using the KDIII-500 electron tensile testing machine (Shenzhen Kaiqiangli Testing Instruments Co., Ltd, China) at room temperature. The rectangular strip-shaped specimens were extended at a crosshead speed of  $50 \text{ mm min}^{-1}$ . The tensile property values reported represent an average of the results from tests run on three specimens.

### 2.4.3. Thermal analysis

Calorimetric studies were carried out on a DSC Q200 thermal analyzer (TA Instruments) using  $\text{N}_2$  as a purge gas ( $50 \text{ mL min}^{-1}$ ) at scan rate of  $10 \text{ }^\circ\text{C min}^{-1}$ . The samples ( $\sim 5 \text{ mg}$ ) were tested in hermetic TA aluminium pans.

#### 2.4.4. Degradation test

Degradation of the samples was carried out in PBS solution at 37 °C<sup>13</sup>. At various intervals of time, the film was taken out and washed with distilled water and dried to a constant weight in vacuum. Weight remaining was monitored gravimetrically and determined using the following equation:

$$\text{Weight remaining (\%)} = M_d/M_i \times 100 \quad (2)$$

Where  $M_i$  is the initial mass of dried sample and  $M_d$  is the final mass of dried sample after incubation.

### 3. Results and Discussion

#### 3.1. Gel behavior of samples

Crosslinking and chain scission of polymers induced by EB irradiation are generally simultaneous phenomena and the ratio of these two events determines the net effect of the process. Usually, in most polymers one of the general processes dominates, either crosslinking or degradation<sup>6</sup>. It was reported that irradiated Polymer containing 3 wt.% TAC can give higher gel content<sup>14</sup>, so the dosage of TAC and TAPE chosen in this study were both 3 wt.% relative to D,L-PEG. The changes of the gel fraction of D,L-PEG in the presence of PFM versus irradiation dose are shown in Fig. 3.

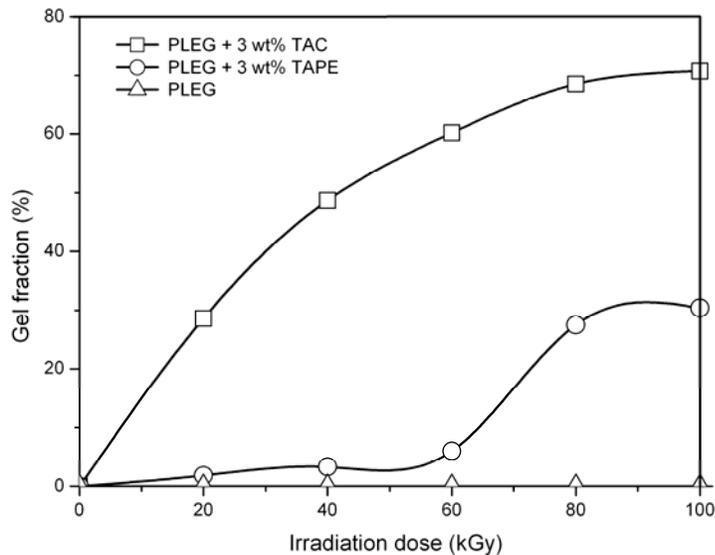


Fig. 3. The effect of irradiation dose on the gel fraction of samples

It can be seen that gel was not formed for irradiated pure D,L-PEG within the absorption dose range of 20-100 kGy. However, the gel fraction of D,L-PEG containing PFM increased significantly. The gel fraction was 70.7 % and 29 % by adding 3 wt.% of TAC and TAPE,

respectively, at irradiation dose of 100 kGy. This is probably contribute to the sufficiently high amount of polymer radiacals produced that react with monomers at a dose of 100 kGy. The effect of the TAC accelerated initial increase in gel content with the dose. After approximately 80 kGy, the effect began to level off for D,L-PLEG. But the gel fraction of D,L-PLEG containing TAPE was low and varied indistinctively before the dose of 60 kGy. It is also observed that TAC gave much higher gel content in radiation-induced crosslinking of D,L-PLEG in comparison with TAPE at the same dose. This is probably due to the presence of three functional groups (C=C) and a cyclic unit (cyanuric ring) of TAC that achieves a greater steady three-dimensional network by irradiation than that of aliphatic TAPE<sup>15</sup>. It is well known that when bulk polymers are irradiated, the dominant reactions and the final products depend strongly on the geometrical arrangements of the polymer molecules<sup>6</sup>.

### 3.2. Tensile properties

Fig. 4 shows the variation of tensile strength with irradiation dose of the samples. It was found that before irradiation the tensile strength of D,L-PLEG/TAC was higher than that of D,L-PLEG/TAPE. But after irradiation, the tensile strength of D,L-PLEG/TAC increased much more compared to that of D,L-PLEG/TAPE. This is attributed to the formation of crosslinking, which can improve the tensile strength of samples. The tensile strength of D,L-PLEG/TAC and D,L-PLEG/TAPE was increased with the increase of irradiation dose up to 48 MPa and 28 MPa at dose of 80 kGy and 60 kGy, respectively, and decreased with further increase of dose. This is probably due to the increase of crosslinking density at early stage, and after reaching a maximum, the higher irradiation dose led to degradation and destroyed the network structure. Therefore, Electron beam (EB) irradiation is a very convenient and efficient method to improve the tensile strength of D,L-PLEG obviously through crosslinking technique.

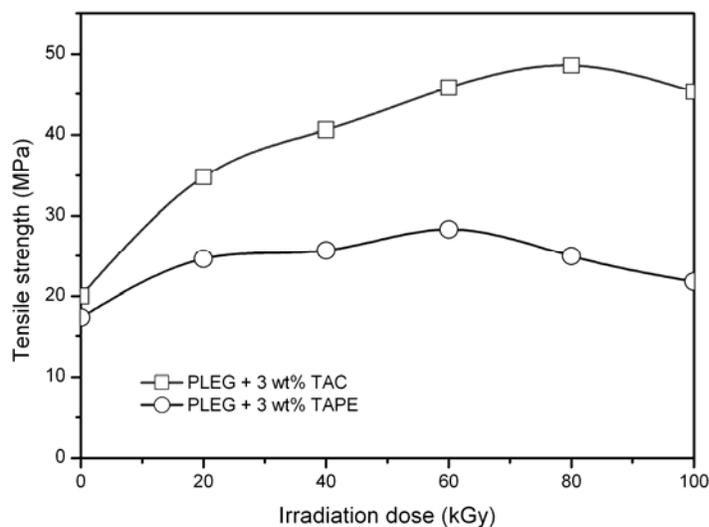


Fig. 4. The effect of irradiation dose on the tensile strength of samples.

The variation of elongation at break versus absorbed dose is shown in Fig. 5. It was found clearly that the elongation at break of two kinds of samples decreased rapidly with the increase of irradiation dose. This is attributed to the formation of radiation crosslinking network in the polymer, which restricted the mobility of the molecular chain during drawing<sup>16</sup>.

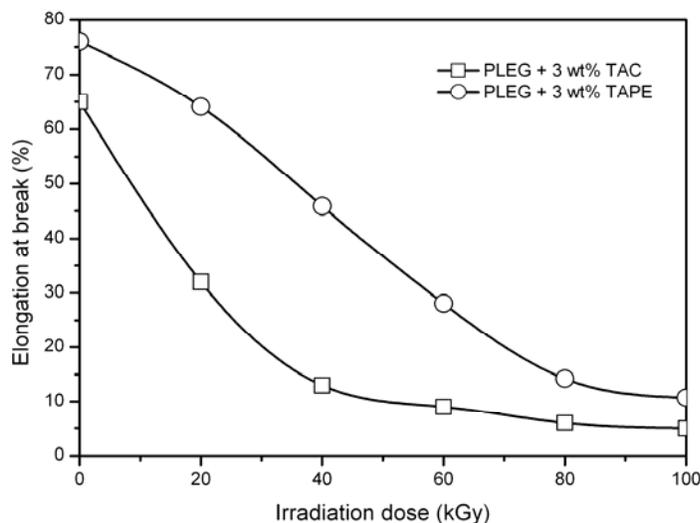


Fig. 5. The effect of irradiation dose on the elongation at break of samples.

### 3.3. Thermal properties

The quantitative evaluation of the thermal transitions of radiated D,L-PEG/TAC samples with various doses. Fig. 6 shows DSC heating curves of the crosslinked D,L-PEG. The original D,L-PEG (a) showed a glass transition temperature ( $T_g \sim 28^\circ\text{C}$ ), then a small exothermic peak of crystallization around  $101^\circ\text{C}$ , followed by a weak melting peak ( $T_m \sim 131^\circ\text{C}$ ), which was similar to the results reported by Wang et al.<sup>12</sup>. However, Curve (b) and (c) showed only an endothermic peak around  $T_g$ , without any peak of crystallization and melting. Meanwhile,  $T_g$  was found to be  $30^\circ\text{C}$  and  $32^\circ\text{C}$  for D,L-PEG/TAPE and D,L-PEG/TAC compounds irradiated at 60 kGy, respectively. This means that D,L-PEG was crosslinked when it was mixed with 3 wt.% of TAC irradiated at those two doses. D,L-PEG molecules were mostly fixed by crosslinks in amorphous region. And  $T_g$  of samples increased with an increasing number of crosslinks<sup>17</sup>.

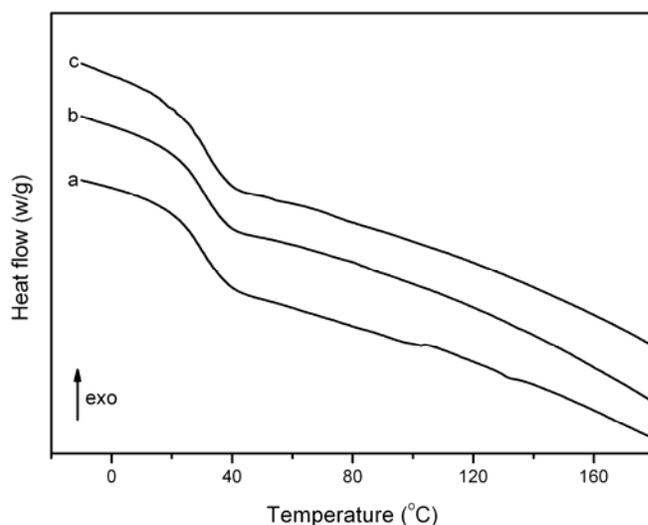


Fig. 6. DSC heating curves of pure D,L-PEG (a); D,L-PEG/TAPE (b) and D,L-PEG/TAC (c) irradiated at 60 kGy.

### 3.4. Degradation test of crosslinked D,L-PEG

The degradation test is a convenient method for evaluating the rate of degradability of polymers. The effect of irradiation dose on the degradation of samples is shown in Fig. 7. Weight remaining of the unirradiated D,L-PEG treated for 480 h was ca. 68 wt.% and that for 960 h was ca. 49 wt.%. This is attributed to the hydrophilic natures of PEG, which solubilized larger molecular weight fragments than would be soluble for the homopolyester itself<sup>18</sup>. On the other hand, PEG increased the accessibility of water to the polymer matrix, this ensured bulk degradation of D,L-PEG. Once D,L-PEG/TAC and D,L-PEG/TAPE irradiated at 80 kGy, the weight of the remaining polymers incubated for 960 h suddenly increased up to ca. 76 wt.% and ca. 70 wt.%, respectively. This is due to the introduction of crosslinking network between molecular chains, which can retard degradation obviously<sup>15</sup>.

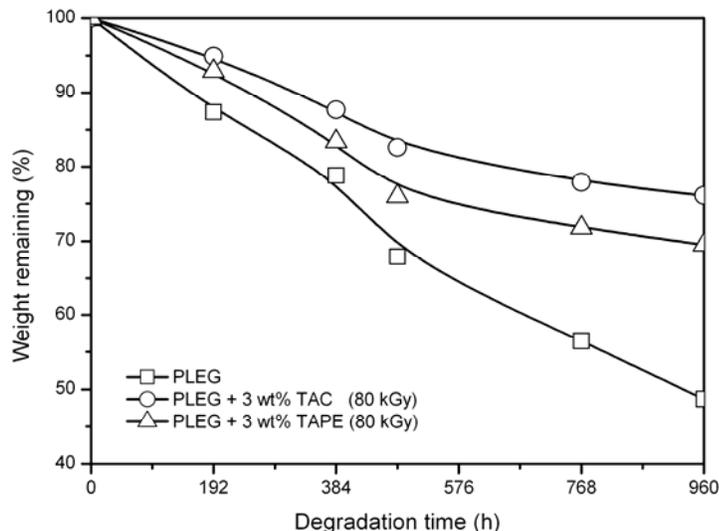


Fig. 7. The effect of irradiation dose on the degradability of samples.

#### 4. Conclusion

The study has demonstrated that D,L-PLEG copolymer was synthesized successfully using low-cost raw materials and melt polycondensation, and it is feasible that D,L-PLEG was radiation-induced crosslinked using low energy electron beam in the presence of TAC and TAPE as crosslinking agents. The gel fraction results indicated that TAC-compounded D,L-PLEG was crosslinked more efficiently than TAPE-compounded D,L-PLEG. Compared with the pure D,L-PLEG, the mechanical and thermal properties of crosslinked D,L-PLEG were improved because of wide formation of radiation-induced crosslinking network in samples. And the introduction of crosslinking network also retard its degradation. Consequently, the addition of a few percent of TAC and TAPE significantly affects the physical properties of the EB treated D,L-PLEG.

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