Effect of an eco-friendly plasticizer on rheological, thermal and mechanical properties of biodegradable poly(propylene carbonate)

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ABSTRACT

A novel plasticizer poly(diethylene glycol adipate) (PDEGA) was synthesized via polyesterification reaction using diethylene glycol and adipic acid as raw materials. A series of poly(propylene carbonate) (PPC) blends were prepared by direct melt compounding with PDEGA as plasticizer. The miscibility, morphology, rheological properties, thermal behavior, and mechanical properties of the blends were investigated. The blends was an partially miscible system with PDEGA uniformly dispersed in PPC matrix. Rheological study concluded that both unplasticized and plasticized PPC exhibited a slightly shear thinning behavior at all angular frequency regions. Viscosities of blends decreased as PDEGA content was increased due to increasing in chain mobility in the system. The plasticization decreased the glass

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transition temperature, which was reflected in a lower tensile strength and improved elongation at break. The pyrolytic decomposition activation energies of PPC and PPC/10wt% PDEGA were estimated via Flynn-Wall-Ozawa method.

1. Introduction

It is well known that the white pollution caused by petroleum-based materials has become an international environmental problem, and the shortage of petroleum resources has driven efforts to produce biodegradable or bio-based materials. Additionally, global warming, known as the greenhouse effect, is caused mostly by the massive release of carbon dioxide (CO₂) into the atmosphere [1]. Thus, the incorporation of CO₂ into materials as a mean of sequestration has attracted scientific and practical interests recently as a mean to reduce greenhouse gas pollution and overcome shortages in classical fuel supplies.

Recently much effort has been made to develop biodegradable polymers from renewable sources, such as poly(lactic acid) (PLA) [2], polycaprolactone (PCL) [3], poly(3-hydroxybutyrate) (PHB) [4], poly(propylene carbonate) (PPC) [5], thermoplastic starch (TPS) [6] and so on. Poly(propylene carbonate) (PPC) is a promising and biodegradable polymer prepared by polymerization of CO₂ with propylene oxide [7, 8]. It possesses excellent adhesion to cellulosic substrates and improved lubricity so that it has been used in binders [9], brazing pastes [10], and solutions, propellants [11] and diamond cutting tools [12]. Moreover, PPC is enzyme degradable [13], biocompatible [14] and readily processible [15]. It can also

completely combust to produce only non-toxic carbon dioxide and water. However, it is brittle which leads to its limited applications. Blending with a low-mass molecular weight plasticizer or other polymers has often been carried out to improve certain properties of biodegradable polymers and to meet various practical requirements [5, 16-21].

Poly(diethylene glycol adipate) (PDEGA) is a novel plasticizer, which was synthesized in our laboratory. It has nontoxic and solvent resistance. Using nontoxic biodegradable macromolecular plasticizer is helpful to our environment [22]. In our previous work, we investigated the effect of PDEGA on the mechanical properties and thermal behaviors of PLA [23]. The results showed that PDEGA was an ideal plasticizer for PLA, and PDEGA plasticized blends exhibited good mechanical properties, and a lower glass transition temperature. However, no reports existed about PPC plasticized by PDEGA and its properties. PDEGA is a polymer of low volatility. So, PDEGA is chosen as a plasticizer for PPC. And we hope to obtain the plasticized PPC with lower glass transition temperature and high elongation at break which could be used to produce the casting film. In this study, PDEGA was melt blended with biodegradable PPC using a melt mixer. Differential scanning calorimetry (DSC), thermogravimetric analysis, tensile test, rheometer and scanning electronic microscopy (SEM) were used to investigate the effects of PDEGA on the thermal, mechanical, dynamic viscoelastic, rheological and morphological properties of the PPC/PDEGA blends.

2 Experimental

2.1 Materials

PPC was supplied by Taizhou Bangfeng Plastic Co., Ltd. (China). The number average molecular weight (M_n) and polydispersity index (PDI) of the purified PPC were determined by GPC as 1.50×10^5 g/mol and 4.32, respectively. The chemical structure for PPC is presented in Scheme 1.

PDEGA was synthesized via polyesterification reaction using diethylene glycol and adipic acid as raw materials in our laboratory. In addition, tetra-*n*-butyl titanate and isooctanol were used as a catalyst and chain-ending reagent for the reaction, respectively, which were purchased from the Sinopharm Chemical Reagent Co., Ltd. PDEGA had molecular weight (M_w) of 3,096 g/mol and polydispersity of 1.46 by GPC analysis. The chemical structure for PDEGA is presented in Scheme 2.

Scheme 1. The chemical structure for poly(propylene carbonate).

Scheme 2. Synthesis of poly(diethylene glycol adipate) from adipic acid and diethylene glycol.

2.2 Sample preparation

Before processing, PPC was dried in vacuum oven at 45 °C for 8 h. PPC/PDEGA blends with several selected weight ratios (100/0, 95/5, 90/10, 85/15 and 80/20) were prepared by using a Haake batch intensive mixer (Haake Rheomix 600, Karls-ruhe, Germany) with a batch volume of 50 ml. The melt compounding was performed at 170 °C and a screw speed of 50 rpm during a total mixing time of 5 min, until the viscosity had reached a nearly constant value. After mixing, all the samples were cut into small pieces and then were hot-pressed at 170 °C for 5 min followed by cold-press at room temperature to form the sheets with thickness of 1 mm. The compression molding steps were carried out carefully in order to obtain the same treatment for every sample.

2.3 Characterization

The cryo-fractured surfaces of the PPC/PDEGA blends selected alcohol removal of PDEGA component. The etching time was 30 min. Cryo-fractured surfaces of PPC/PDEGA blends were characterized by a field emission scanning electron

microscope (XL–30 ESEM FEG, FEI Co., USA). All samples were coated with a thin layer of gold of about 10 nm and an accelerating voltage of 10 kV was used to produce the SEM photographs.

Melt flow index (MFI) is the melt flow rate index, expressed in grams, extruded isothermally in 10 min under constant load through a die of standard dimensions [24, 25]. MFI of the neat PPC and PPC/PDEGA blends were determined with a μ PXRZ-400B melt-flow indexer (Changchun, China) equipped with a standard die. The die had a smooth straight bore with a diameter of 2.0955 ± 0.0051 mm and a length of 8.000 ± 0.025 mm. The measurements were performed according to ASTM D 1238-82. The investigated temperature was 170 °C.

Rheological measurements of the blends were conducted with the rheometer (TA Instruments Co., AR 2000ex, USA) at 170 °C. Frequency sweep for neat PPC and the PPC/PDEGA blends was carried out under nitrogen using 25-mm plate-plate geometry. The gap distance between the parallel plates was 0.9 mm for all tests. The sheet samples were about 1.0 mm in thickness. Storage modulus (G'), loss modulus (G''), and complex viscosity (η^*) were measured in the angular frequency sweep experiments performed over a frequency range of 0.1–100 rad/s. The η' , the real part of the complex viscosity and the η'' , the imaginary part of the complex viscosity were calculated according to the following equations:

$$\eta' = G''/\omega \quad (1)$$

$$\eta'' = G'/\omega \quad (2)$$

The glass transition temperature (T_g) of neat PPC and PPC/PDEGA blends was

determined by differential scanning calorimetry (DSC) (TA Instruments DSC Q20 USA) on the specimens sliced from compression molded samples. Samples (about 5–8 mg) were placed and sealed in aluminum pans. The samples were then heated from –60 up to 100 °C at 10 °C/min.

The T_g s of the components were also studied by dynamic mechanical analysis (DMA, TA Instruments Co., DMA, Q800, USA). The dimensions of the samples were 20 mm × 4 mm × 1 mm. The experiment was carried out in tension mode at a constant heating rate of 3 °C/min and a frequency of 1 Hz, from –80 to 80 °C.

The thermal stability of materials was measured by thermogravimetric analysis (TGA, Perkin-Elmer TGA-7, USA) simultaneous thermal analysis instrument. The PPC/PDEGA samples with weight of 10 ± 0.2 mg were heated from room temperature to 600 °C at 10 °C/min under nitrogen.

PPC and PPC/10wt% PDEGA were subjected to the TGA in a nitrogen atmosphere. The experiments were conducted at four different heating rates (5, 10, 20, 30 and 40 °C/min) from room temperature to 600 °C.

The uniaxial tensile tests were carried out at room temperature on an 1121 testing machine (Instron Corporation, USA). Specimens (20 mm × 4 mm × 1 mm) were cut from the previously compression-molded sheet into a dumbbell shape. The measurements were conducted at a cross-head speed of 50 mm/min at 23 ± 2 °C according to ASTM D638-2008. At least five runs for each sample were measured, and the results were averaged.

3 Results and discussion

3.1 Miscibility of PPC/PDEGA blends

Scanning electron microscope is an instrument used to analyze the miscibility of the blends. The etched surfaces of binary PPC/PDEGA blends are shown in Fig. 1. As observed in images, there were many microvoids in the PPC/PDEGA blends. The dispersed phase was finely and homogenously dispersed in the matrix of the blends with different content of PDEGA. With the increasing of PDEGA content, the diameters of the dispersed PDEGA phase were further broadened. Summing up the above phenomena, the PPC/PDEGA blends might be classified as immiscible or partially miscible. Similar microvoids were also observed in PLA/PDEGA, PHBV/ESO, PLA/PPG , and PLA/ESO blends [22, 26–28].

The efficiency and compatibility of plasticizer requires a similarity in solubility parameters between plasticizer and polymer [29, 30]. The miscibility of plasticizer and PPC could be estimated by comparing the solubility parameters(δ) of two molecules. The closer the δ values of the two molecules, the greater is the compatibility between PPC and plasticizer, and this plasticizer could decrease the glass transition temperature of PPC much more effectively. The solubility parameter δ can be calculated using the methods of Hoy [31]:

$$\delta = \frac{\rho \sum F_i}{M_0} \quad (3)$$

where δ is the solubility parameter, ρ is the density, M_0 is the molecular weight, and F_i represents the group molar attraction constants. The corresponding data is shown in Table 1. The calculated the solubility parameter of PDEGA was close to that of PPC,

which indicated that they should be partially miscible in blending. The effect of PDEGA on mechanical and thermal properties of PPC could also be explained in terms of solubility parameters of the plasticizer and polymer.

3.2 Rheological analysis

MFI index shows changes in material flowability which indicates changes in material structure. The MFI of neat PPC and PPC/PDEGA blends are determined, and the results are shown in Fig. 2. It could be noted that the MFI was gradually increased with the increasing of PDEGA content. Although the neat PPC had the MFI of 0.22 g/10 min, the MFI increased to 1.25 g/10 min when the PDEGA content was 20 wt%. In this work, PDEGA was a new type of plasticizer for PPC. When PDEGA was added in PPC, the PDEGA molecule diffused into PPC matrix by penetrating, which would make matrix slip and flow easier.

Dynamic melt rheological properties of neat PPC and PPC/PDEGA blends were measured to elucidate the melt processability of the blends. The complex viscosity (η^*) of neat PPC and PPC/PDEGA blends as a function of angular frequency (ω) are shown in Fig. 3. It could be observed that neat PPC exhibited shear thinning at all angular frequency region. Compared with neat PPC, the complex viscosities of PPC/PDEGA blends also showed a shear-thinning tendency the tendency became stronger with increasing PDEGA content. The complex viscosities of blends were substantially lower than that of neat PPC and decreased with the increasing of PDEGA content, which was a typical plasticizing effect. It indicated that the PDEGA

in the blends acted as plasticizer and caused the increase of the free volume and the chains' mobility of PPC [32]. The decreased complex viscosity of the blend meant that the processability of PPC was improved apparently.

The rheological data are analyzed using the Cole-Cole plot, representing the relationship between the real (η') and the imaginary (η'') parts of complex viscosity. [33]. It has been reported that the plot can be used to analyze the miscibility of polymer blends [34–36]. A smooth, semicircular shape of the plotted curves would suggest good compatibility, i.e., phase homogeneity in the melt, and any deviation from this shape shows a nonhomogeneous dispersion and phase segregation due to immiscibility [37]. The Cole–Cole plots for neat PPC and PPC/PDEGA blends were presented in Fig. 4. It could be observed that PDEGA and PPC were miscible (or at least finely dispersed) in the all PPC/PDEGA blends, as could be evidenced from the smooth semicircular shape of the plots. The fine dispersion was also demonstrated in Fig. 1.

The corresponding dynamic storage modulus (G') and loss modulus (G'') for neat PPC and PPC/PDEGA blends are shown in Figs. 5(a) and (b), respectively. As expected, the G' and G'' of PPC decreased with increasing PDEGA content over the entire angular frequency range. The lower G' values of the blends were supposed to be originated from the decrease in molecular entanglement in the blends. The PPC/PDEGA blends had lower G'' values than that of neat PPC over the entire frequency range. This was due to the fact that G'' represented the viscous behavior (i.e., the amount of energy dissipated), and the addition of PDEGA to the PPC

produced a material with the lowest energy dissipation. From the view of miscibility of blends, the interaction between blends decreased to a certain extent at higher PDEGA content. Hence decreasing in amount of energy dissipated of blends melting with all load resulted in the decreased loss modulus [38].

3.3 Dynamic mechanical properties

The loss modulus (E'') of the neat PPC and PPC/PDEGA blends were measured by DMA and the curves were shown in Fig. 6. The glass transition temperature (T_g) is an important indicator for mobility of chain segment. Therefore, plasticizing efficiency has been evaluated by the decrease of T_g as a function of plasticizer content [39, 40]. The T_g s are obtained from the E'' peak temperature and the T_g s values are given in the Table 2. Neat PPC showed a sharp E'' peak at around 33.4 °C. As the PDEGA was added, the E'' peak for the 95/5 PLA/PDEGA blend shifted to a lower temperature at 25.0 °C. It indicated that PDEGA as a plasticizer could increase segmental mobility of the PPC chains, which decreased the T_g of PPC. With the further increasing PDEGA content, two distinct glass transitions could be distinctively identified. The high temperature transitions around 20 °C could be associated with the glass transition of PPC and the low temperature transitions around -60 °C could be attributed to the relaxation of PDGEA. In addition, the two distinct glass transitions shifted to lower temperature as well with increasing amounts of PDEGA. The results indicated that the PPC/PDEGA blend was partially miscible, which is consistent with the analysis of solubility parameters.

3.4 Thermal properties

Thermal properties of neat PPC and PPC/PDEGA blends were investigated by means of DSC and TGA. The DSC thermographs of neat PPC and PPC/PDEGA blends are shown in Fig. 7 and the corresponding parameters are given in the Table 2. It could be seen that a single T_g appeared for the PPC/PDEGA blend at a lower temperature than that for neat PPC and it gradually decreased to lower temperature with increasing PDEGA content in the blend. When 5 wt% PDEGA was added, the T_g decreased from 32.6 °C of neat PPC to 24.6°C and down to 14.2 °C when 20 wt% of PDEGA was added. Such decrease in T_g was commonly observed for plasticized PPC systems, indicating that PDEGA was an effective plasticizer for PPC.

The effect of the plasticizer on the thermal stability often takes into account when studying a plasticized polymer. One of most accepted methods to study the thermal properties of polymeric materials is thermogravimetry. The integral (TGA) and derivative (DTG) thermogravimetric curves provide information about the nature and extent of degradation of the polymeric materials. The TGA and DTG traces for PPC and PLA/PDEGA blends in nitrogen atmosphere are shown in Fig. 8 and the corresponding parameters are given in the Table 2. The thermal degradation behavior of various samples are compared using the initial decomposition temperature (T_{onset}) and the temperature of maximum rate of weight loss (T_{max}) in order to understand the effects of PDEGA on the thermal degradation process of PPC. The data are listed in Table 2. Neat PPC started to decompose at 255.4 °C. After that, the weight loss

increased quickly, and the maximum degradation rate occurred at 268.4 °C. The T_{onset} of PDEGA was 218.6 °C. The thermal degradation process of all blends had two stages in the temperature ranges of 230–260 °C and 260–350 °C, as shown in Fig. 8. The first stage might belong to the degradation of PPC and the second stage was the degradation of PDEGA. The T_{onset} and T_{max} of PPC shifted systematically to lower temperatures with the usage of PDEGA plasticizer. This shift was globally more important when the amount of PDEGA was higher. For example, a shift from 255.4 °C to 233.5 °C and from 268.4 °C to 237.1 °C was observed for the T_{onset} and T_{max} of the 80/20 PPC/PDEGA blend, respectively. The decrease of the PPC thermal stability was mainly because of the presence of PDEGA as plasticizer. PDEGA promoted a decrease in thermal stability by its action to intersperse itself around polymers and by breaking polymer-polymer interactions, which were predicted in the lubricity theory and gel theory of plasticization [41].

The dynamic TGA method was a promising tool to unravel the mechanisms of physical and chemical processes that occur during polymer degradation. Generally, for polymer degradation, all kinetic studies assume that the isothermal rate of conversion da/dt is proportional to the concentration of reacted material. The rate of conversion can be expressed by the following basic rate equation:

$$\frac{d\alpha}{dt} = k(T) f(\alpha) \quad (4)$$

where $f(\alpha)$ and $k(T)$ are function of conversion and temperature, respectively.

$k(T)$ is often modeled successfully by the Arrhenius equation:

$$k(T) = A \exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

where $E\alpha$ is the pyrolytic decomposition activation energy, A the pre-exponential factor and R the gas constant.

$f(\alpha)$ depends on the particular decomposition mechanism. The simplest and most frequently used model for $f(\alpha)$ in the analysis of TGA data is:

$$f(\alpha) = (1 - \alpha)^n \quad (6)$$

where n is the order of reaction.

Insertion of eqs (5) and (6) into eq (1) gives

$$\frac{d\alpha}{dt} = \beta \frac{d\alpha}{dT} = A(1 - \alpha)^n e^{-\frac{E\alpha}{RT}} \quad (7)$$

Flynn-Wall-Ozawa method [42] eq (7) is integrated using Doyle's approximation [43], and the result of the integration after taking logarithms is:

$$\log \beta \frac{d\alpha}{dT} \Rightarrow \log \frac{A}{R} - \log (1 - \alpha)^n - \frac{E\alpha}{2.315RT} \quad (8)$$

Thus, it is used to determine the activation energy for given values of conversion. The activation energy for different conversion values can be calculated from a $\log \beta$ versus $1/T$ plot.

The thermal degradation kinetic analysis of PPC and PPC/10wt% PDEGA were determined with Flynn-Wall-Ozawa method. The Flynn-Wall-Ozawa plots are shown in Fig. 9. Figures 9 (a) and (b) show that the fitting lines are straight lines with a good correlation coefficient r , which indicates the applicability of Flynn-Wall-Ozawa to the systems in the conversion range investigated. The $E\alpha$ of samples are shown in Table 3. Evidently, the $E\alpha$ at the all stage of the degradation decreased with the addition of the PDEGA. And the $E\alpha$ of PPC/10wt% PDEGA was lower than those of pure PPC at the same weight loss. It could be inferred that the early degradation of PDEGA caused a

decrease in the activation energy.

3.5 Mechanical properties

The goal of adding plasticizer to PPC is to enhance plastic elongation and reduce brittleness while maintaining maximum polymer strength and stiffness. The stress-strain curves of neat PPC and PPC/PDEGA blends are shown in Fig. 10. It could be seen that neat PPC fractured at a lower tensile strain and no yield point was observed. The blends presented a yield point before the break and a subsequent plastic deformation which suggested that the addition of PDEGA was an effective means to improve the tensile toughness of PPC matrix. The stress-whitening behavior of the blends was observed during tensile deformation. The results were in agreement with previous literature reports about the PLA/PDEGA blends [23].

The tensile strength, Young's modulus, and elongation at break for neat PPC and PPC/PDEGA blends with different PDEGA content are shown in Table 4. The tensile strength decreased from 37.1 MPa for neat PPC to 22.2 MPa for the 90/10 PPC/PDEGA blend. The increase of PDEGA content to 20 wt% further decreased the yield stress to about 14.1 MPa. Some authors have reported similar decreased strength in other blends plasticized by PDEGA. The tensile strength for the PLA/PDEGA blends decreased as the content of PDEGA increased [23]. The tensile strength was dependent on the chemical bond forces and interaction between molecules, in particular the hydrogen bonding. The lower interaction between PPC macromolecules caused the decrease in the tensile strength for the blends when PDEGA was added in

the blend.

Neat PPC exhibited an elongation at break value of 7.3% and it significantly increased with the addition of PDEGA. When the PDEGA content was 15 wt%, the elongation at break increased to a maximum value (1300%), which was about 178 times higher than that for neat PPC. In our previous works, we found that PDEGA could improve the flexibility of PLA by acting as a plasticizer [23]. The elongation at break for the PLA/PDEGA blends was slightly higher than that for neat PLA (4.5%), and increased from 4.6 to 480% as the PDEGA content increased from 5 to 20 wt%. For the PPC/PDEGA blends, the plasticizer weakened the interaction between polymer macromolecules and improved the flexibility of polymer chains, which could cause a great increase in elongation at break for the polymer. For the reason, the elongation at break for the PPC/PDEGA blends had a sharp increase when PDEGA was added.

The Young's modulus for neat PPC was 1380 MPa, which was higher than that for the blends. As the PDEGA content increased, the tensile modulus gradually decreased. At the PDEGA of 20 wt%, the Young's modulus reached the lowest value (93.7 MPa). The results presented agreed with our previous work where the tensile modulus for the PLA/PDEGA blends decreased as the loading of PDEGA increased [23]. The Young's modulus was the ratio between the stress and the applied deformation which was also mainly depended on the chemical bond forces and the interaction between macromolecules. Therefore, the Young's modulus for the blends exhibited the slight decrease in higher loading of PDEGA similar with the change of the tensile strength.

4 Conclusions

The ultimate objective of this study is to develop PDEGA as a biodegradable plasticizer for improving the mechanical properties of PPC. It was found that the PPC/PDEGA blend was partially miscible. The PPC/PDEGA blends exhibited lower storage modulus and complex viscosity than that for neat PPC, because of the plasticization effect of PDEGA. PDEGA significantly lowered the glass transition temperature of PPC and increased the segmental mobility of the PPC chains by plasticization. PDEGA promoted a decrease in thermal stability by its action to intersperse itself around polymers and by breaking polymer–polymer interactions. Tensile tests revealed that PDEGA markedly improved the flexibility of the PPC matrix. The elongation at break for the blends increased sharply as the PDEGA content was increased. At the PDEGA content of 20 wt%, the elongation at break for the blends attained a maximum, which was about 178 times than that for neat PPC. In conclusion, plasticized PPC were achieved and we developed these plasticizers really taking a satisfying effect on PPC.

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Figure captions

Fig. 1. SEM micrographs of cryogenically fracture surfaces of PPC/PDEGA blends: (a) 95/5, (b) 90/10, (c) 85/15, and (d) 80/20.

Fig. 2. Variations of MFI for neat PPC and PPC/PDEGA blends.

Fig. 3. Plots of complex viscosity (η^*) versus angular frequency (ω) for neat PPC and PPC/PDEGA blends.

Fig. 4. Plots of Cole-Cole for neat PPC and PPC/PDEGA blends.

Fig. 5. Plots of (a) dynamic storage modulus (G') and (b) loss modulus (G'') versus angular frequency (ω) for neat PPC and PPC/PDEGA blends.

Fig. 6. Loss storage modulus versus temperature traces of PPC/PDEGA blends with different PDEGA contents.

Fig. 7. DSC thermograms of neat PPC and PPC/PDEGA blends.

Fig. 8. Effect of PDEGA on the thermal stability of PPC: (a) TGA and (b) DTG.

Fig. 9. Flynn–Wall–Ozawa plots at the following different weight losses of (a) PPC and (b) PPC/10wt% PDEGA.

Fig. 10. Stress-strain curves of neat PPC and PPC/PDEGA blends.

Table 1

Some parameters related to the solubility parameter δ of PPC and PDEGA.

	ρ (g/cm ³)	M_0 (g/mol)	δ (J/cm ³) ^{1/2}
PPC	1.20	102	19.4
PDEGA	1.05	200	18.9

Table 2

Thermal properties of neat PPC and PPC/PDEGA blends.

PPC/PDEGA (w/w)	T_g^a , PPC (°C)	T_g^b , PPC (°C)	T_g^b , PDEGA (°C)	T_{onset} (°C)	T_{max} (°C)
100/0	32.6	33.4	-	255.4	268.4
95/5	24.6	25.0	-	238.9	246.4
90/10	19.1	18.2	-57.4	237.1	240.9
85/15	17.3	15.2	-62.3	235.0	239.7
80/20	14.2	10.8	-67.2	233.5	237.1
0/100	-	-	-	218.6	393.3

^a Obtained from DSC analysis.^b Obtained from DMA analysis.

Table 3

Activation energies of PPC and PPC/10wt% PDEGA by Flynn–Wall–Ozawa method.

Conversion α	PPC		PPC/10wt% PDEGA	
	E(KJ/mol)	r	E(KJ/mol)	r
0.1	136.8	0.9985	117.3	0.9987
0.2	126.7	0.9984	112.8	0.9981
0.3	122.7	0.9978	110.3	0.9977
0.4	117.6	0.9977	107.7	0.9964
0.5	112.8	0.9946	104.5	0.9937
0.6	107.0	0.9933	104.4	0.9926
0.7	100.3	0.9879	98.9	0.9882
0.8	88.5	0.9814	90.8	0.9819

Table 4

Mechanical properties of neat PPC and PPC/PDEGA blends.

PPC/PDEGA (w/w)	Young's Modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)
100/0	1080±23	37.1±2.8	7.3±0.5
95/5	364±10	23.5±1.9	780±23.6
90/10	183±12	22.2±2.6	1200±30.2
85/15	130±8.6	22.6±1.5	1300±31.4
80/20	93.7±3.9	14.1±0.9	1300±30.6

Figure 1

(a)

Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 4000x SE 8.7 1

5 μ m

(b)

Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 4000x SE 8.8 1

5 μ m

(c)

Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 4000x SE 8.7 1

5 μ m

(d)

Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 4000x SE 9.6 1

5 μ m

Figure 2

Figure 3

Figure 4

Figure 5a

Figure 5b

Figure 6

Figure 7

Figure 8a

Figure 8b

Figure 9a

Figure 10