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High-Gas-Barrier and Biodegradable PPC-P/PBAT Composite Films Coated by Poly(vinyl alcohol)/borax Complexes

Jiangtao Deng [1], Shuangshuang Yue [2], Min Xiao [2], Sheng Huang [2], Shuanjin Wang [2], Dongmei Han [1,2,*] and Yuezhong Meng [1,2,3,4,*]

[1] School of Chemical Engineering and Technology, Sun Yat-sen University, Guangzhou 510275, China; dengjt23@mail2.sysu.edu.cn
[2] The Key Laboratory of Low-Carbon Chemistry & Energy Conservation of Guangdong Province/State Key Laboratory of Optoelectronic Materials and Technologies, School of Materials Science and Engineering, Sun Yat-sen University, Guangzhou 510275, China; yss05010301@126.com (S.Y.); stsxm@mail.sysu.edu.cn (M.X.); huangsh47@mail.sysu.edu.cn (S.H.); wangshj@mail.sysu.edu.cn (S.W.)
[3] Institute of Chemistry, Henan Academy of Sciences, Zhengzhou 450052, China
[4] College of Chemistry, Zhengzhou University, Zhengzhou 450001, China
* Correspondence: handongm@mail.sysu.edu.cn (D.H.); mengyzh@mail.sysu.edu.cn (Y.M.)

Abstract: Degradable and high-barrier plastic packaging materials draw more attention with the development of a social economy and the demands of environmental protection. In this study, poly(propylene carbonate phthalate) (PPC-P) and poly(butylene adipate-co-terephthalate) (PBAT) blends with different ratios were designed and prepared, marked as PPC-P/PBAT. Chain extenders were introduced into the blends, and the mechanical properties, thermal properties, and barrier properties of the composites were studied. The 75PPC-P/PBAT with 2% extenders represent the best performance. The addition of the chain extender has significantly improved the thermal stability and tensile elongation of PPC-P/PBAT. On this basis, the PPC-P/PBAT composite film was coated with PVA and borax using the dipping and pulling method. The oxygen barrier properties have been further improved for the composite film with a coating layer. Considering the characteristics of biodegradability and a high-barrier property, the 75PPC-P/PBAT/2MDI@Gly blend coated with 2 wt% PVA and 3 wt% borax exhibits potential as a superior food/pharmaceutical plastic packaging material with excellent tensile and barrier properties.

Keywords: high barrier; biodegradable; PPC-P; composites

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Citation: Deng, J.; Yue, S.; Xiao, M.; Huang, S.; Wang, S.; Han, D.; Meng, Y. High-Gas-Barrier and Biodegradable PPC-P/PBAT Composite Films Coated by Poly(vinyl alcohol)/borax Complexes. *Surfaces* **2024**, *7*, 517–528. https://doi.org/10.3390/surfaces7030034

Academic Editor: Felix H. Schacher

Received: 7 June 2024
Revised: 17 July 2024
Accepted: 22 July 2024
Published: 1 August 2024

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1. Introduction

In the past few decades, with the rapid development of the economy, more and more goods need safe and reliable packaging that can attract customers. Traditional high-barrier plastic packaging materials, such as polypropylene (PP), polyethylene terephthalate (PET), poly (vinylidene chloride) (PVDC), vinyl alcohol copolymer (EVOH), etc., are non-degradable, and their use has caused great effect on the environment. According to the World Bank, global plastic waste production reached 12% of the total solid waste in 2016 [1]. With the enhancement of environmental awareness, people gradually turn their attention to degradable packaging materials [2–4]. Biodegradation of biodegradable polymers is defined as the chemical breakdown of substances, which is carried out through the enzymatic action of microorganisms, resulting in changes in chemical composition, and mechanical and structural properties, forming metabolites that are environmentally friendly substances such as methane, water, biomass, and carbon dioxide [5].

Recently, our group introduced phthalic anhydride (PA) into the propylene oxide (PO) and CO_2 copolymerization system and successfully synthesized the ternary copolymerization product PPC-P, and adjusted the polymer sequence and structure by selecting a suitable catalyst. The results show that the addition of phthalic anhydride effectively improved the

thermal and mechanical properties of PPC, which can be embodied by the glass transition temperature reaching more than 47 °C and the tensile strength being higher than 37.6 MPa. In addition, the synthesized PPC-P has a satisfactory degradation rate under standard composting conditions. However, the elongation at break of the PPC-P decreases sharply to 6%, showing brittleness [6,7]. PBAT is a biodegradable aliphatic aromatic polyester formed from adipic acid, 1,4-butanedial, and dimethyl terephthalate. Its high flexibility, thermal stability, and good processability are ideal materials for plastic film and plastic bags [8–10], but its low stiffness and weak tensile strength and modulus still need to be improved to achieve a wider range of industrial applications. Based on the advantages and disadvantages of PPC-P and PBAT, PPC-P/PBAT composites can be coupled with the advantages of each component to obtain composite materials with excellent comprehensive properties.

Since PPC-P and PBAT are incompatible, 4,4′-diphenylmethane diisocyanate (MDI) and glycerol (Gly) were selected as chain extenders in this study. Firstly, the -NCO groups of MDI can react with the -OH in Gly to form a cross-linking point; then, the -OH in the blend can further react with the remained-NCO groups, improving the compatibility between two polymers and the mechanical properties of the composites. In order to further improve the barrier properties of the composites, a PVA–borax oxygen barrier coating was constructed by the method of layer self-assembly, considering PVA as a common barrier layer material [11,12]. This technique makes it easy to combine the versatile features of two or more building blocks without complex processing [13,14]. The design idea of this study is shown in Figure 1. By evaluating the mechanical, thermal, optical, and barrier properties of the composites, this study will contribute to the potential applications for degradable high-barrier packaging materials.

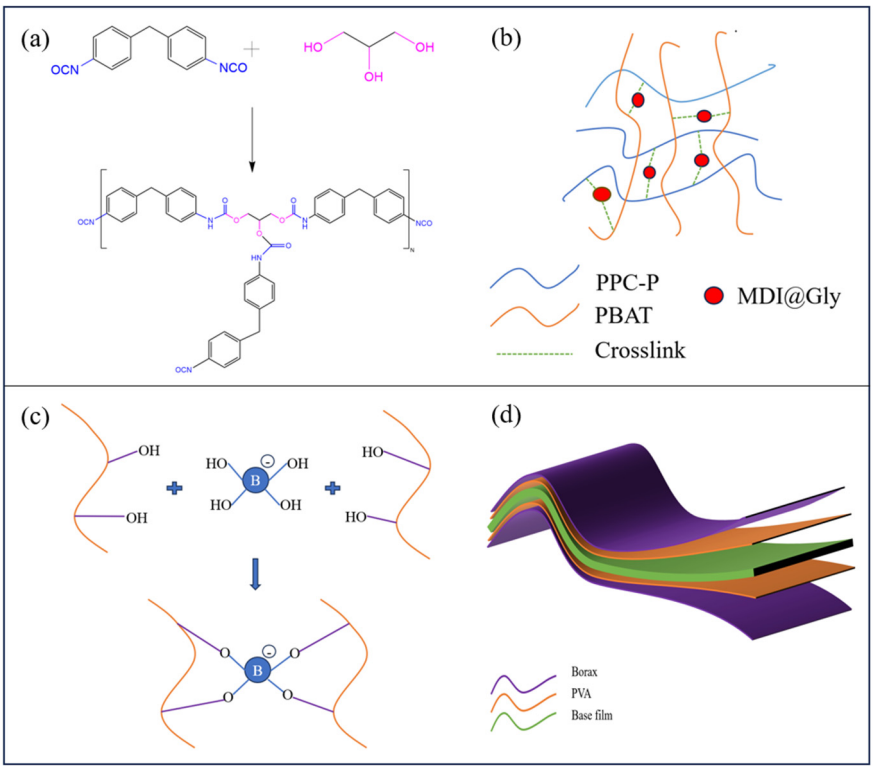


Figure 1. (**a**) Chain extension of MDI and glycerol; (**b**) schematic diagram of composites with chain extender; (**c**) PVA/borate ion complexes; (**d**) schematic illustration of the preparation of PVA–borax-coated PPC-P/PBAT films.

2. Materials and Methods

2.1. Materials

Poly(propylene carbonate phthalate) (PPC-P) was provided by Shandong Lianxin Environmental Protection Technology Co., Ltd., Zibo, China, with an average molecular weight (Mn) = 78.6 kg/mol and a molecular weight distribution (PDI) = 1.35. Poly(butylene adipate-co-terephthalate) (PBAT) (Brand A400) was bought from, Zhuhai JinFa Technology Co., Ltd., Zhuhai, China, and partially dissolved in THF; Mn = 45.8 kg/mol, PDI = 1.89, and crystallinity was 21.46%. Polyvinyl alcohol (PVA, Mn = 500 g/mol, alcoholysis 88%), 4,4′-diphenylmethane diisocyanate (MDI), glycerin (Gly), and borax were all supplied by Shanghai Macklin Biochemical Technology Co., Ltd., Shanghai, China, without further processing.

2.2. Preparation of PPC-P/PBAT Blends

PPC-P and PBAT were dried in a blast oven at 80 °C for 12 h, and then fed into the torque rheometer according to different mass ratios of PPC-P to PBAT (75/25, 50/50, and 25/75) for melting at 160 °C with a processing speed of 70 r/min for 20 min. At the same time, two series of PPC-P, PBAT, and chain-extender composites with mass ratios of 75/25/2 and 75/25/4 were prepared under the same processing conditions, where the chain extender was MDI and glycerin had a molar ratio of 3:1. For comparison, pure PPC-P and PBAT were prepared under the same processing conditions. After the above products were obtained, the dumbbell-shaped sample for tensile testing and the sample film for barrier property testing were prepared by the flat vulcanizing machine. The molding temperature was 160 °C and the molding pressure was 10 MPa for 5 min. The common sample was named xPPC-P/PBAT/yMDI@Gly, where x represents the weight percentage of PPC-P in PPC-P/PBAT and y represents the weight amount of MDI@Gly in every 100 parts of the PPC-P/PBAT blend.

2.3. Preparation of the Coating Layer

A series of PVA solutions with different concentrations were prepared by dissolving the polymer in deionized water at 90 °C for 2 h. Borax and sodium hydroxide with a mass ratio of 2:1 were added into a mixture of 95 vol. % methanol and 5 vol. % deionized water, which was magnetically stirred at 40 °C for 4 h. The undissolved borax was then filtered out to prepare the borax methanol base solution. The xPPC-P/PBAT/yMDI@Gly film was coated with 1~8 wt% PVA aqueous solution and then vertically hung in a fume hood for 10 min. Then, the composite film was transferred to an oven to be dried at 80 °C for 1 h. Subsequently, the PVA-coated film was cooled to room temperature in a dryer, and then dipped into the borax methanol base solution using the dipping method for 5 s and hung in a fume hood for 10 min. Finally, the composite film was moved to an oven to be dried at 80 °C for 1 h, when the preparation of the coating was completed.

2.4. Characterization

2.4.1. Mechanical Properties

According to GB/T1040.3-2006, a dumbbell-shaped sample with dimensions of 25 mm × 4 mm × 1 mm was obtained by hot pressing with a plate vulcanizing press. A tensile test was conducted on the materials using a universal testing machine (CMT 4204, SANS, Qingdao Dongfang Jiayi electronic Technology Co., Ltd., Qingdao, China) at a temperature of 25 °C, a humidity of 50% ± 5%, and a tensile speed of 5 mm/min during the test. Each sample was tested in at least five trials, with the mean value taken as the result. Prior to testing, the samples were placed in the test environment for 24 h to ensure that the samples were the same temperature and humidity as described above.

2.4.2. Thermogravimetry

TGA measurements were performed in a Perlin Elmer Pyris Diamond TG/DTA analyzer (PerkinElmer, Waltham, MA, USA) under a nitrogen atmosphere at a heating rate of 10 K/min in the temperature range of 30–600 °C.

2.4.3. Thermal Transition Performance

The glass transition temperature (T_g), cold crystallization temperature (T_c), and melting temperature (T_m) of the samples were measured using a differential scanning calorimeter (DSC, Model 204, Netzsch Scientific Instruments Trading (Shanghai) Ltd., Shanghai, China). The sample was initially elevated from room temperature to 180 °C at a rate of 10 K/min and maintained at 180 °C for a period of 3 min. Subsequently, the temperature was reduced to −100 °C in liquid nitrogen at a rate of 10 K/min, and maintained at −100 °C for 3 min. Once more, the temperature rose to 180 °C at a rate of 10 K/min.

2.4.4. Microscopic Morphology

The 1 mm thick sample was soaked in liquid nitrogen for 1 min and fragmented to produce a cross section. The specimen was dried and then sprayed with gold by a high-performance ion sputtering instrument (108, Cressington Scientific Instruments, Watford, UK). The gold spraying time was set at 30 s, with a gold spraying current of 25 mA; then, the micro-morphology of the sample fractured surface was observed and photographed by a scanning electron microscope (SEM, JSM-6330F, JEOL Ltd., Tokyo, Japan).

2.4.5. Optical Properties

The optical properties of the film were tested using a transmittance/fog meter (WGT-S, Shanghai Shengguang Instrument and Meter Co., Ltd., Shanghai, China). This meter uses a tungsten halogen lamp that emits light in the wavelength range of 350 nm to 760 nm.

2.4.6. Barrier Properties

An oxygen permeability tester (Y210, Guangzhou Biaoji Packaging Equipment Co., Ltd., Guangzhou, China) was used to determine the oxygen transmission rate and oxygen permeability coefficient of the film samples. The test standard was GB/T 19789-2005, and the experimental temperature was 23 °C.

The water vapor permeability tester (MOCON3/61, Ametek Trading (Shanghai) Co., Ltd., Shanghai, China) was used to determine the water vapor transmission rate of the film samples. The test standard was ASTM F-1249, and the experimental temperature was 23 °C.

The thickness of the film was measured by a thickness gauge, and 8 points were uniformly taken on each sample to measure the thickness and calculate its average value.

3. Results

3.1. Mechanical Properties

The mechanical tensions of the prepared PPC-P/PBAT blends were studied. The tensile properties of PPC-P/PBAT blends with different mass ratios are shown in Figure 2a, and pure PPC-P and PBAT were tested under the same conditions as a comparison. The mechanical properties above are summarized in Table 1. As a high-barrier and biodegradable polymer, PPC-P is hard and brittle at room temperature with a tensile strength of approximately 42.4 MPa and an elongation at break of only 7.3%. On the contrary, PBAT shows a moderate strength and high elongation at break of 1100%. The incorporation of flexible PBAT into PPC-P was found to be an effective method of enhancing the blend's flexibility [15]. Nevertheless, the addition of a small quantity of PBAT does not significantly enhance the toughness of the blend until the proportion of PBAT exceeds 50%. At this point, the toughness of the blend is markedly improved. Meanwhile, the tensile strength of PPC-P exhibits a gradual decline in the presence of PBAT. This indicates that the constituent

polymers in the blend system are incompatible, which results in phase separation and tensile property deterioration [16].

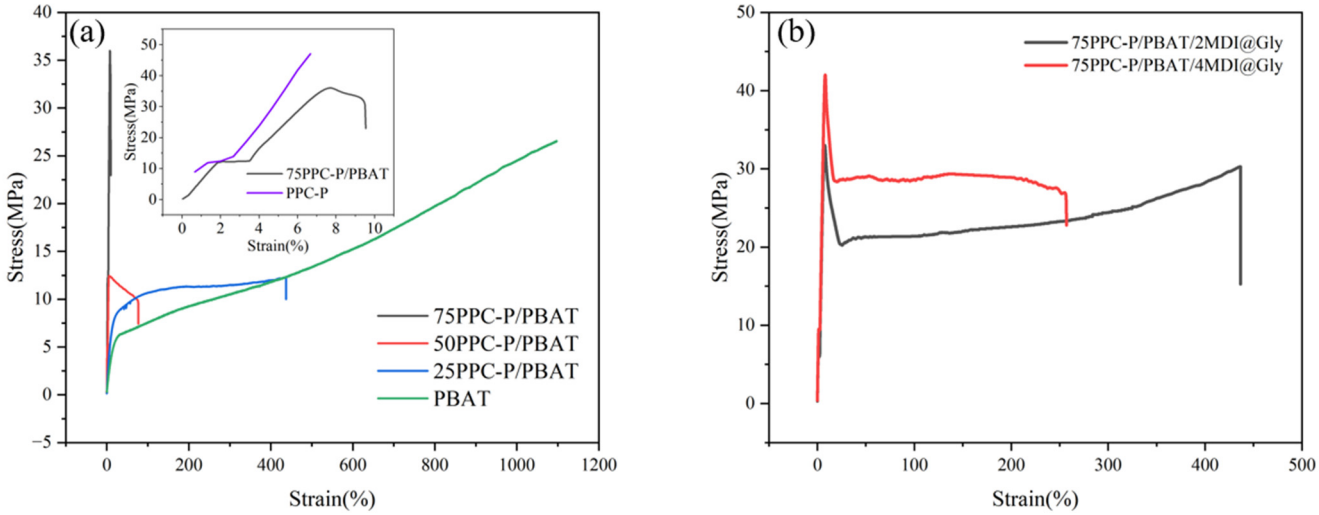


Figure 2. Tensile curves of (**a**) PPC-P/PBAT blends and (**b**) PPC-P/PBAT/MDI@Gly composites.

Table 1. Mechanical properties of the polymers and composites.

PPC-P/PBAT (wt%/wt%)	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (MPa)
100/0	42.4	7.3	1650
75/25	35.9	9.6	605
75/25/2 [a]	33.0	435	471
75/25/4 [b]	43.1	256	612
50/50	12.2	77	382
25/75	11.3	437	318
0/100	26.4	1100	225

[a]: 75PPC-P/PBAT/2MDI@Gly; [b]: 75PPC-P/PBAT/4MDI@Gly.

Hence, in order to enhance the interfacial compatibility, MDI@Gly has been used as a reactive compatibilizer due to the presence of -NCO groups that react with the end hydroxyl group of PPC-P and PBAT under heat and high shear stress during extrusion [17]. The 75PPC-P/PBAT blends exhibit the optimum mechanical properties; therefore, this composition was chosen to fabricate composites in the presence of MDI@Gly. Figure 2b depicts the tensile properties of the PPC-P/PBAT/MDI@Gly composites. For the sample 75PPC-P/PBAT/2MDI@Gly, the elongation at break increased from 9.6% to 435% with the incorporation of 2 wt% MDI@Gly. The results demonstrate that MDI@Gly, as a chain extender and chemical cross-linking agent, effectively enhanced the interfacial compatibility between PPC-P and PBAT. However, when the content of the chain extender was further increased to 4 wt%, the elongation at break dropped sharply to 256%. This may be due to the formation of a greater number of interconnected network-like structures, which made it difficult for the molecular chains to move. It is noteworthy that the elongation at break of the blend after the addition of the chain extender is comparable to that of the 25PPC-P/PBAT blend (11.3 MPa), while maintaining high strength (33 MPa). On the whole, the incorporation of the chain extender significantly enhances the mechanical properties of blends.

3.2. Thermal Properties

3.2.1. Analysis of Crystallization and Melting Behavior

The DSC curves of PPC-P, PBAT, and xPPC-P/PBAT/yMDI@Gly are shown in Figure 3a, and the main thermal performance parameters measured during this process are summarized in Table 2. PPC-P is an amorphous polymer with only one T_g of 54.3 °C, and no melting points were recorded in the DSC curves. PBAT is a soft elastomeric material with a T_g of only −28.7 °C, and a broad endothermic melting peak centered (T_m) at 115.9 °C. The prepared PPC-P/PBAT blends all represent two T_g values, corresponding to PBAT and PPC-P, respectively. This indicates the formation of a two-phase system due to incompatibility between the two constituent polymers. In addition, the T_g of PPC-P exhibits a slight increase with the incorporation of PBAT. This can be attributed to the crystalline phase of PBAT, which restricts the movement of PPC-P molecular chain segments [18]. On the other hand, amorphous PPC-P can penetrate into the amorphous region of PBAT and reduce the molecular stack density, which promotes the mobility of molecular chain segments, so the crystallinity of PBAT decreases with the increase in PPC-P content.

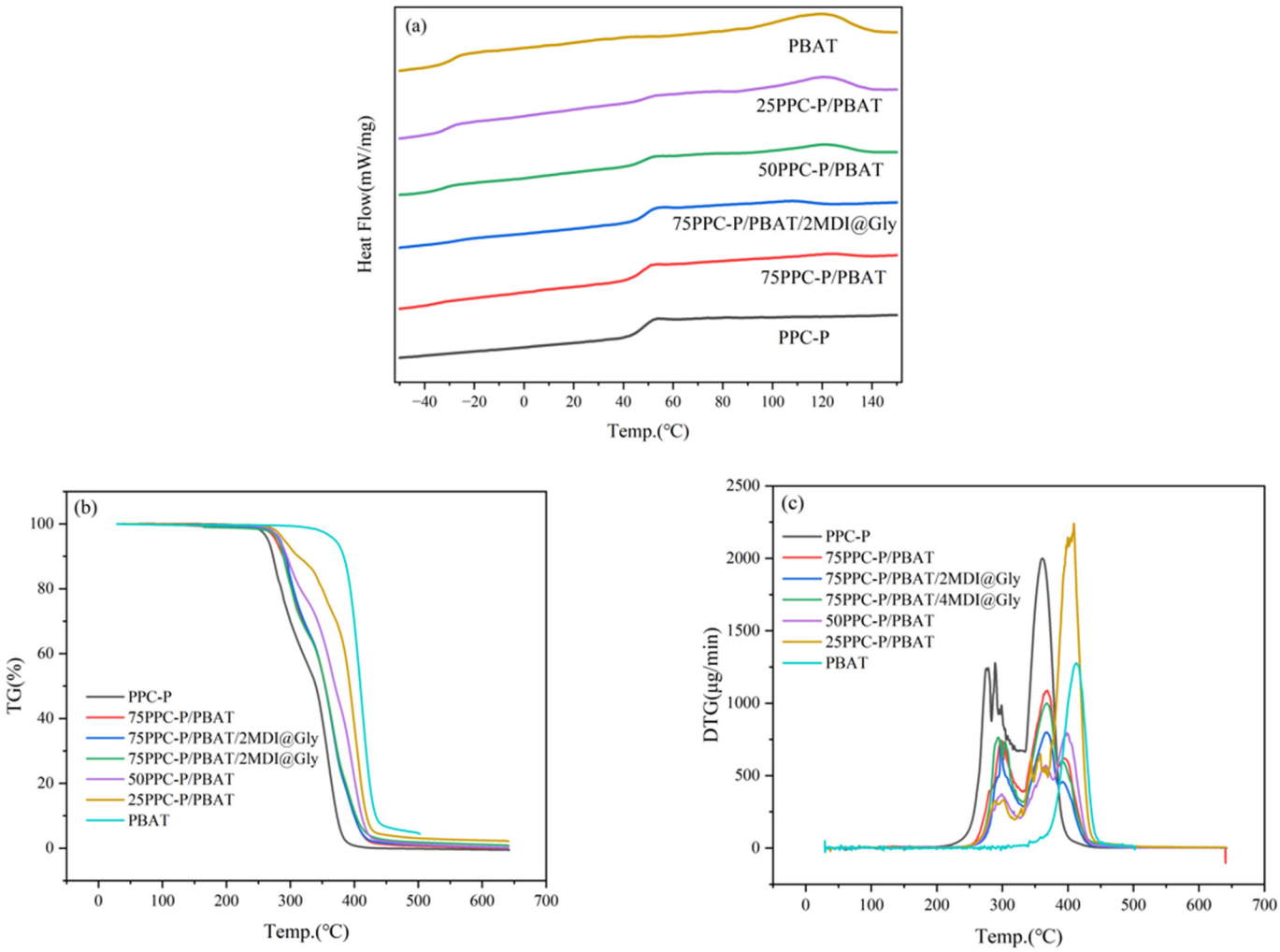


Figure 3. Thermal property curves of PPC-P/PBAT blends and PPC-P/PBAT/MDI@Gly composites: (**a**) secondary temperature rise curves of DSC, (**b**) TG curves, and (**c**) DTG curves.

Table 2. DSC analysis characteristic data of the polymers and composites.

PPC-P/PBAT (wt%/wt%)	$T_{g,PBAT}$ (°C)	$T_{g,PPC-P}$ (°C)	T_m (°C)	ΔH_f (J/g)	χ_c (%)
100/0	-	54.3	-	-	-
75/25	−35.3	55.4	124.4	4.73	16.60
75/25/2	−28.2	57.0	102.7	2.11	7.40
75/25/4	−27.7	55.6	104.2	2.43	8.53
50/50	−32.2	56.0	118.4	8.85	15.53
25/75	−31.1	49.7	120.8	14.59	17.06
0/100	−28.7	-	115.9	24.47	21.46

Further incorporation of the chain extender results in the T_g values of the two phases tending to be close to each other, which indicates improved compatibility between the interfaces. In addition, the melting point and melting enthalpy (ΔH_f) of the blends were observed to decrease with the addition of the chain extender, as shown in Table 2. Besides, the crystallinity (χ_c) of PBAT in the blend also decreased with the introduction of the chain extender, demonstrating a plasticizing effect [19]. This was also the internal reason for the increase in elongation at break.

3.2.2. Thermal Stability Analysis

The TGA and DTG curves for PPC-P, PBAT, and their blends are shown in Figure 3b,c. It is evident that the thermal degradation of virgin PPC-P and PBAT starts at 265.1 °C and 370.0 °C, respectively, and the T_{dmax} temperatures are noticed at 278.5 °C and 360.7 °C (corresponding to the polycarbonate and polyester chain segments of PPC-P), and 413.4 °C (PBAT), as shown in Table 3. Due to the incompatibility of the two phases, the PPC-P/PBAT blends exhibit three distinct decomposition peaks. It is noteworthy that the T_{dmax1} of 75PPC-P/PBAT is markedly elevated following the incorporation of PBAT. The T_{dmax1} of 75PPC-P/PBAT is 19.8 °C higher than that of PPC-P, which can be attributed to the "thermal shielding effect" of the more heat-resistant and partially crystalline PBAT phase, which necessitates a higher temperature for the unzipping reaction of the PPC fragment in the PPC-P phase. Consequently, the incorporation of a chain extender into the blend results in a notable improvement in thermal stability (the $T_{d5\%}$ of the blend with 2% and 4% chain extender was 7.4 °C and 4.2 °C higher than that without the chain extender, respectively).

Table 3. Thermal stability of the polymers and composites [a].

PPC-P/PBAT (wt%/wt%)	$T_{d5\%}$ (°C)	T_{dmax} (°C)		
		T_{dmax1}	T_{dmax2}	T_{dmax3}
100/0	265.1	278.5	360.7	-
75/25	276.9	298.3	368.9	394.5
75/25/2 [b]	284.3	297.6	366.5	392.2
75/25/4 [c]	281.1	293.7	367.4	392.0
50/50	283.9	299.3	366.6	398.7
25/75	290.4	295.6	366.0	409.1
0/100	370.0	-	-	413.4

[a]: Determined by TGA tests, T_{d5} = 5% weight loss temperature, T_{dmax} = maximum weight loss temperature. [b]: 75PPC-P/PBAT/2MDI@Gly; [c]: 75PPC-P/PBAT/4MDI@Gly.

3.3. Microstructure Characterization

The microstructure of the brittle section of the polymers and composites was characterized by SEM, as shown in Figure 4. When the PPC-P content is less than 50 wt% (Figure 4a,b), the blends mainly show a continuous structure without obvious phase separation. In order to improve the barrier properties, the PPC-P content in the blends was further increased to 75 wt%, considering the contribution of the PPC-P component to the barrier properties is decisive. With the increase in PPC-P content, PBAT is uniformly distributed

in the PPC-P substrate as a dispersed phase (Figure 4c), thereby forming a "sea-island" structure with clear phase interface. With the introduction of the chain extender MDI@Gly, the phase interface of the 75PPC-P/PBAT/2MDI becomes blurred, indicating that the compatibility between PPC-P and PBAT is improved (Figure 4d). The coating situation of the barrier layer is shown in Figure 4e. It can be seen that a small amount of borax contacts the base film through PVA, and most of borax is evenly interspersed in the PVA layer to play a cross-linking role and the thickness of the coating layer is about 5 μm, thereby improving its oxygen resistance.

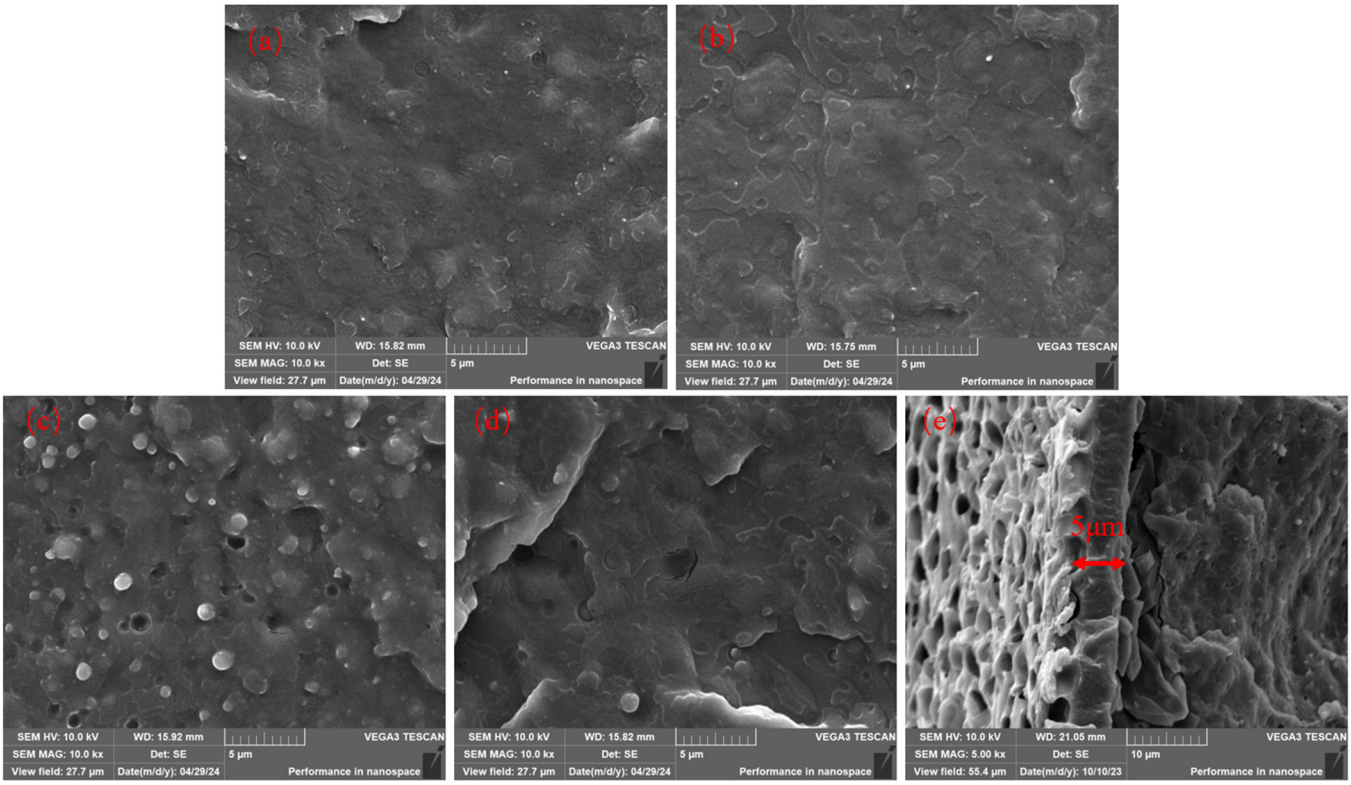


Figure 4. Cross sections of PPC-P/PBAT blends and coatings: (**a**) 25PPC-P/PBAT; (**b**) 50PPC-P/PBAT; (**c**) 75PPC-P/PBAT; (**d**) 75PPC-P/PBAT/2MDI@Gly; (**e**) 75PPC-P/PBAT/2MDI@Gly coated with PVA–borax.

3.4. Optical Properties

The transparency of plastic packaging materials is an important consideration for consumers, the appearance of the films is shown in Figure 5. It can be seen in Table 4 that both the base film and the coated film belong to transparent materials (transmittance > 80%). The base film itself exhibits a high degree of fog due to the incompatibility of PPC-P/PBAT, but this fog level remains relatively stable after coating. The above shows that the PVA–borax coating does not greatly affect the optical properties of the film. By combining the comprehensive properties, the composite films show potential application in the packaging field.

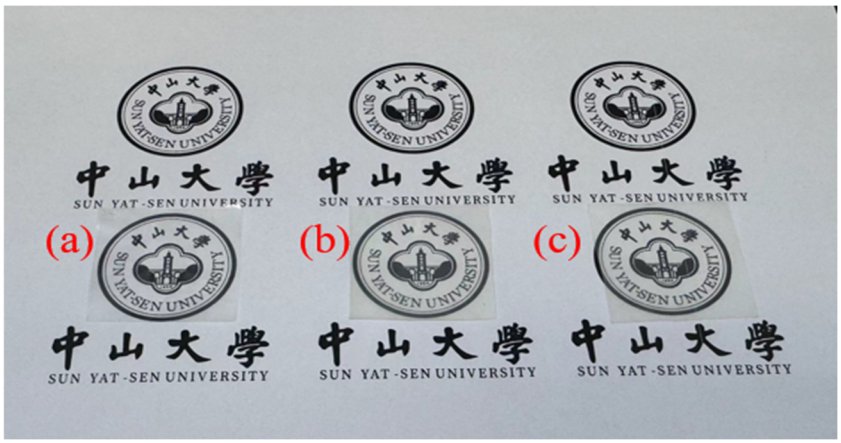


Figure 5. Macroscopic optical image of film: (**a**) PPC-P; (**b**) 75PPC-P/PBAT/2MDI@Gly coated by 2 wt% PVA; (**c**) 75PPC-P/PBAT/2MDI@Gly coated by 2 wt% PVA and 3 wt% borax.

Table 4. Optical properties of thin films.

Films	Transparency (%)	Fog (%)
75PPC-P/PBAT	86.3	38.5
75PPC-P/PBAT/2MDI	85.3	42.9
PVA–borax coating [a]	84.9	43.2

[a]: The base films is 75PPC-P/PBAT/2MDI@Gly.

3.5. Barrier Properties

Water and oxygen barrier properties are an important index for evaluating food packaging materials [20]. The barrier properties of polymers are highly dependent on their chemical and morphological structures, and oxygen permeability usually follows the free volume theory, that is, a higher free volume usually leads to higher oxygen permeability [21]. However, the permeability of water vapor depends more on the interaction between water molecules and polymers, and the degree of cohesion between molecules [22]. Therefore, the water and oxygen barrier properties of PPC-P/PBAT-based films were tested and the results are listed in Table 5. It can be seen that PPC-P has excellent water and oxygen barrier properties, while PBAT has poor barrier properties. Therefore, the barrier performance of the blend deteriorates with the increase in PBAT content in the component. It shows that the samples with the chain extender added have better barrier properties than the samples without the chain extender with the same mass ratio, possibly because the molecular chain becomes more dense after the chain extension reaction, and oxygen and water molecules need to pass through the film through more tortuous paths, thus improving the barrier properties [23].

Table 5. Barrier properties of the films.

PPC-P/PBAT (wt%/wt%)	Thickness (μm)	OTR ($cm^3/[m^2/day]$)	OP ($\mu m \cdot cm^3/[m^2/day]$)	Thickness (μm)	WVTR ($g/[m^2/day]$)	WVP ($\mu m \cdot g/[m^2/day]$)
100/0	116	12	1392	124	0.111	13.8
75/25	185	17	3217	174	0.190	33.2
75/25/2	217	8.2	1790	231	0.206	47.5
50/50	252	68	17,136	255	0.443	113
25/75	230	128	29,440	222	0.963	214
0/100	253	180	45,540	262	1.087	285

In order to further improve the barrier properties of the films, 75PPC-P/PBAT/2MDI@Gly was used as the base film, and a series of coating layers were built and their barrier prop-

erties were evaluated. Firstly, PVA solution of different concentrations was coated on the base film, and its oxygen barrier properties are shown in Figure 6a. This shows the addition of the PVA coating greatly helps the oxygen barrier properties, and with the increase in PVA concentration, that is, the increase in the thickness of the coating layer, the oxygen barrier property of the film is further improved. However, the trend of improving the oxygen barrier is gradually decreasing. After comprehensive consideration, 2 wt% PVA was selected for borax cross linking. As is shown in Figure 1c, $B(OH)_4^-$ can be formed after hydrolysis of borax under alkaline conditions, which could cross link with the -OH site on PVA. After coating only with 1 wt% borax, the oxygen permeation coefficient (OP) of the film was reduced from 470 μm·cm^3/[m^2/day] to 89 μm·cm^3/[m^2/day], and the oxygen resistance performance of the film was further improved by increasing the concentration of borax (Figure 6b). Especially when coated with 3 wt% borax, the oxygen transmission rate (OTR) value was much lower than 0.02 cm^3/[m^2/day], and the lower detection limit of the instrument was 0.02 cm^3/[m^2/day]. Where the test film thickness was 172 μm, the calculated OP was less than 3.5 μm·cm^3/[m^2/day]. However, when the concentration of borax continued to increase, the oxygen inhibition performance decreased to the contrary, which may be due to the excessive local borax concentration during the coating process, resulting in an uneven barrier layer and resulting defects [24]. PPC-P has excellent water resistance; the water vapor transmission rate (WVTR) was 0.111 g/[m^2/day], considering the thickness of the sample and the water vapor permeation coefficient (WVP) was calculated to be 13.8 μm·g/[m^2/day], as presented in Table 5. By blending with PBAT, the water resistance of the blends began to deteriorate, and the deterioration became more and more intense with the increase in PBAT amounts. Nevertheless, 75PPC-P/PBAT still maintained good water resistance. In brief, the introduction of chain extenders could increase the oxygen inhibition performance effectively, but seems not to have a positive effect on improving the water resistance, even through the addition of a coating layer. At room temperature, the composite film is insoluble in water, ethanol, and methanol. In view of this and its excellent oxygen and water vapor barrier properties, the composite film has a promising future as a packaging material.

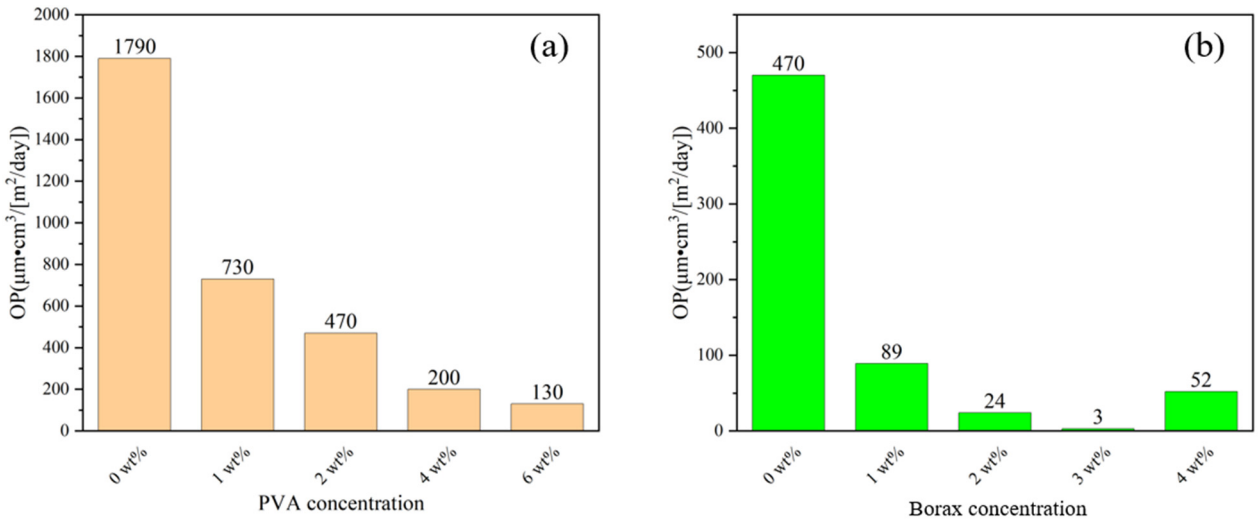


Figure 6. Oxygen barrier properties of the films with coating layer: (**a**) PVA coating layer; (**b**) 2 wt% PVA–borax coating layer.

4. Conclusions

In summary, a series of PPC-P/PBAT blends with different compositions were prepared by blending PPC-P and PBAT, and the mechanical properties of the composite were further improved by the adding chain extender MDI and glycerol. The results show that the composite (weight ratio of PPC-P:PBAT:chain extender = 75:25:2) had good mechanical properties; the tensile strength was 33 MPa, the elongation at break was 435%, and the

barrier properties were good. In order to further improve the barrier properties of the composites, the self-assembly and cross-linking of PVA and borax layers were applied to obtain the composite film. The oxygen barrier performance of the composite film with the coating layer was further improved, and the oxygen transmission rate exceeded the lower limit of the instrument detection for the sample with 2 wt% PVA and 3 wt% borax coating. Therefore, the designed PPC-P/PBAT composite film materials show good barrier properties, mechanical properties, and thermal properties. This study not only greatly broadens the application field of PPC-P, but also provide a reference for promoting the application development of biodegradable, high-barrier, plastic packaging materials.

Author Contributions: J.D.: Conceptualization, Investigation, Validation, Methodology, Formal analysis, Writing—original draft. S.Y.: Investigation, Visualization, Formal analysis. M.X.: Formal analysis, Data curation. D.H.: Investigation, Methodology. S.H.: Investigation, Data curation. S.W.: Conceptualization, Data curation, Writing—review & editing. Y.M.: Conceptualization, Writing—review & editing, Funding acquisition, Supervision. All authors have read and agreed to the published version of the manuscript.

Funding: National Natural Science Foundation of China (Grant No. 22179149); Research and Development Project of Henan Academy of Sciences China (No. 232018002).

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank the National Natural Science Foundation of China (Grant No. 22179149), and the Research and Development Project of Henan Academy of Sciences China (No. 232018002). for financial support of this work.

Conflicts of Interest: The authors declare no competing financial interest.

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