Effect of Low Loading Biodegradable Poly(Ethylene Carbonate) to Physicochemical and Mechanical Properties of Melt-Blended Poly(Lactic Acid)

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ABSTRACT

Poly(lactic acid)/poly(ethylene carbonate) (PLA/PEC) blends with a low ratio range of PEC contents were successfully prepared via the melt blending technique. The objectives of this study are to evaluate the effect of low content of PEC on the PLA and further characterize the blend using torque analysis, Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC) analysis, Fourier Transform Infra-Red (FTIR) analysis, and mechanical properties. The PLA/PEC samples with different ratios, which is PLA98/PEC2, PLA96/PEC4, PLA94/PEC6, PLA92/PEC8, and PLA90/PEC10, are selected in this research. The addition of PEC content in PLA reduced the torque value. The PLA90/PEC10 blends degraded first, and 5 wt% weight loss (Td_5) of the PEC/PLA blends was decreased with PEC, which influences the thermal stability of the blends. The crystallinity of PLA has changed with the addition of 10% of PEC, resulting in the highest crystallinity up to 48.81%, thus influencing the toughness of the blends, giving the PLA a better modulus of toughness, and increasing the elongation at the break due to the plasticizing effect. Slight changes in the absorbance peaks of carbonyl and ether groups have confirmed the interaction between PLA and PEC even at a low loading of PEC. Due to the low loading of PEC content to PLA, the absorbance peak of PLA/PEC blends for the carbonyl group tends to shift towards a neat PLA peak. Thus, low PEC loading is strongly suggested as an alternative to PLA modification in various applications.

Keywords: Biodegradable, low loading, poly(ethylene carbonate), poly(lactic acid), polymer blend

INTRODUCTION

Polymers are large macromolecules containing "monomers," which can be classed based on chain branching, molecular weight, functional groups, and physical properties. Synthetic polymers are common polymers, also known as "biopolymers" (Russell, 2003). Controversies about plastics production and usage are created due to synthetic polymer's production and large-scale use. It is reported that only 10% of all plastic products have been recycled, and the majority of them end up in landfills or are assembled as waste in the environment (Geyer et al., 2017). According to research done by Fushimi & Gaffney (2014), up to 10 billion tonnes of garbage from plastics can be created worldwide every year. It is estimated that the time for decomposition of this plastic waste is 200-400 years. Reducing environmental waste leads to the interest in replacing plastic with more eco-friendly and biodegradable synthetic polymers. The potential solution to minimizing the pollution of plastic and controlling the carbon footprint is by using biodegradable plastic, which is produced by using biodegradable polyesters such as poly(hydroxyalkanoate) (PHA) and poly(lactic acid) (PLA). Poly(lactic acid) (PLA) is a common biodegradable thermoplastic polyester made from the monomers lactic acid and lactide by polycondensation and ring-opening polymerization (ROP) (Wang et al., 2017). PLA has several advantages, such as good physical and mechanical behavior, other than better clarity and barrier properties. However, the limitation of PLA comes into brittleness due to its low toughness, and it also has poor physicochemical and biodegradability properties that need to modify (Nofar et al., 2020). The methods for modification of PLA are chemical copolymerization, plasticization, and polymer mixture. The addition of thermoplastic polyurethane (TPU) improves mechanical strength, resistance impact, and shape memory property (Chen et al., 2017). Moreover, approaches to blending PLA with another type of aliphatic polycarbonate have caught the interest of many researchers. Aliphatic polycarbonate is biodegradable and has better strain hardening in mechanical properties that can help improve PLA properties. One of the attractive aliphatic polycarbonate types is poly(ethylene carbonate) (PEC). PEC is a biodegradable polymer made from carbon dioxide (CO_2) reacting with epoxides through a copolymerization method, having strong biodegradability and biocompatibility (Ramlee & Tominaga, 2019a).

The most used technique in the preparation of polymer blending is physical blending by the extrusion technique. Melt blending of poly(lactide) (PLA) and poly(butylene succinate) (PBS) blends was used to create a new type of biodegradable material with high toughness and strength for fused deposition modeling (FDM) technology (Ou-Yang et al., 2018). Lyu et al. (2020) studied polymer blending for 3D printing applications combining poly (lactic acid) (PLA) and poly(butylene-adipate-co-tere-phthalate) (PBAT).

Polymer blends have also become the most popular thermoplastic filament materials for 3D printing technology. Alternative materials for 3D printing were produced using PLA, PBAT, and nano talc (Prasong et al., 2020). Other than that, the polymer blends of poly(lactic acid) and poly(butylene adipate-co-terephthalate) were examined by Pivsa-Art et al. (2013), with the addition of poly(butylene succinate) (PBS) as a compatibilizer.

The preparation of PLA/PEC blends using the melt blending technique still needs further investigation. The previous research study for this blend was done at the high ratio range for PEC using solvent-based casting. Their research study found that phase separation occurred in the PLA50/PEC50. Therefore, this study focuses on preparing PLA/PEC blends via the melt blending technique with the effect of low-loading PEC on the phase separation of the blends. Since the PEC has limited stock availability due to the high cost, the low loading of PEC has been used in the research. The characterizations, including the torque analysis, Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC) analysis, Fourier Transform Infra-Red (FTIR) analysis, and mechanical properties of the PEC/PLA blends, were investigated.

MATERIALS AND METHOD

Materials

A commercial grade poly(lactic acid) (PLA), grade 3001D pellets (MFI: 22 g/10min) were used, and poly(ethylene carbonate) (PEC) (QPAC®25) with molecular weight, Mw=131,000 was purchased from Empower Materials, USA also being used. Both materials were used without chemical treatment for the preparation of the blends. Before processing, PLA pellets were vacuum dried at 60 ºC for 24 hours to eliminate the moisture content and weighed on a high precision scale. Both polymers were kept in a desiccator prior to the preparation of the blends.

Methods

The melt blending technique was used to prepare the samples of PEC/PLA blends. The PLA/PEC samples at different weight percentage ratios, PLA98/PEC2, PLA96/PEC4, PLA94/PEC6, PLA92/PEC8, and PLA90/PEC10, were premixed prior to melting blending. The melt blending method was prepared using Thermo Scientific (Haake Rheonix OS) with a temperature process of 150°C and 60 rpm for the speed of the screw. All blends were palletized using a granulator after the mixing process. By maintaining 4.29 g of the weight of each pallet's samples, the samples were prepared by hot pressing technique (Model: ComeTech) at a temperature of 160°C for pre-heating and compressed and 50°C for a cooling process under 5 MPa pressure for 10 min. The film was kept in a desiccator before being analyzed.

Characterization

Torque analysis is characterized using Thermo Scientific (Haake Rheomix OS) internal mixer for the melt blending technique. The multiple polymers, PEC and PLA, were mixed using rolls within a closed chamber. The thermogravimetric analyzer (TGA) was used to determine the degradation temperatures of the PLA/PEC blend film (Model: Mettler Toledo). The temperature was characterized by the mass of the sample being measured over time as the temperature changed. All film samples had the same dimensions of 5mm x 5mm x 3mm and were heated at 10°C/min from 30°C to 600°C. The thermal characteristics of the PLA/PEC blend film samples were measured using a Differential Scanning Calorimeter (DSC) (Model: Mettler Toledo). DSC was used to observe enthalpy changes in samples as a function of temperature or time due to changes in physical and chemical characteristics. It was subjected to DSC processes at temperatures ranging from -40°C to 200°C, with a heating rate of 10°C/min. The blends' value of glass transition temperature (T_{g1}) was determined using the heating method. The melting temperature (T_m) of PEC, PLA, and all PLA/PEC blend samples was observed using the temperature at the melting peak's maximum values. The blends' cold crystallization can also be determined by using DSC analysis. The crystallinity of PLA (X_c) is calculated using Equation 1, which is normalized by the PLA weight fraction (X_{PLA}),

$$X_c(\%) = \frac{\Delta H_m}{\Delta H_m^\circ} \, x \, \frac{100}{X_{PLA}} \tag{1}$$

where ΔH_m (J/g) is the melting enthalpy of PLA and ΔH°_m is the theoretical melting enthalpy of a 100 percent crystalline PLA, which is 107 J/g, according to Ramlee and Tominaga (2018). Fourier Transform Infra-Red (FTIR) Perkin Elmer (Model: Spectrum One) was used to observe the FTIR measurement of the PLA/PEC blends film samples. The FTIR readings were taken between 4000 cm^{-1} and 515 cm^{-1}. The tensile strength of materials or all PLA/PEC blends film samples was determined using Universal Tensile Machine Tinius Olson (Model: H50KT). The Universal Tensile Machine was fitted with a 2 kN load cell with ± 0.5% accuracy with the design of the tensile specimens according to the ASTM D882-10. The crosshead speed for the tensile machine ranges from 1 to 500 mm/min. Therefore, the crosshead speed is set to 25 mm/min in this study. A sample from each blend was used to determine the tensile properties. The width of the sample was 25 mm, and the thickness was 0.3 mm, with an area of 7.5 mm^2. After that, the elastic modulus was calculated in the stress-strain curve by taking the slope of the initial linear region.

RESULTS AND DISCUSSION

Torque Analysis

Figure 1 shows the mixing torque analysis as a function of time, and Figure 2 indicates the mixing torque as a function of the composition of PEC.
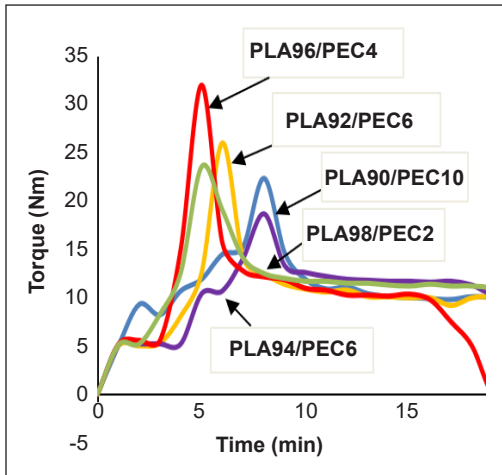
Figure 1. Mixing torque as a function of mixing time at 60 rpm and 150°C
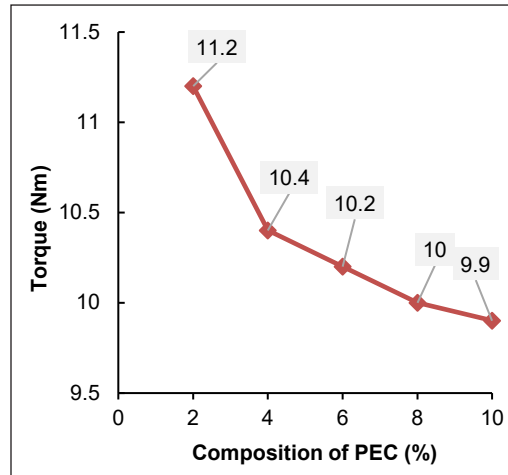
Figure 2. Mixing torque as a function of the composition of PEC in the blends at 15 min

The torque for the blends develops significantly initially due to the input of PLA and PEC pellets into the mixer, then decreases due to the melting of the pellets, and finally remains rather constant, as shown in Figure 1. Zhang et al. (2020) found a similar result in their research of the torque analysis since they found that the melting of PLA pellets and the addition of PUDA-co-BUDA are responsible for the initial peaks and abrupt drops on the torque curves. As demonstrated in Figure 2, the torque values for all blends were obtained based on Figure 1 at a constant time of 15 min (black circle). The torque value for all PLA/PEC blends dropped as the percentage of PEC in the blends increased. It is probably due to the friction caused by the increase in PEC composition, which resulted in a higher resistance on the rotor blades. It can be shown in Figure 1 that PLA96/PEC4 mixed well at 7 min compared to the PLA94/PEC6, which mixed well at 10 min. The initial peaks and abrupt declines on torque curves show the melting of PLA pellets and adding PEC components to the blends.

Based on Figure 2, the torque values decreased with increasing PEC content. According to Gigante et al. (2019), the trend of the torque reduced when the plasticizer, which is poly(butylene succinate) (PBS), was mixed with the PLA. It is also reported by Patti et al. (2020) that the torque value reduction by increasing cellulose composition by 35%, 55%, 68%, and 77%, and the processing time recorded was 25 minutes. Due to the melting of PLA, the torque decreases dramatically, resulting in a fall in melt viscosity (Kamaludin et al., 2020). Thus, the selection processing time was 15 minutes which the PLA and PEC were thoroughly melted and uniformly mixed. According to Xie et al. (2019), PLA and polypropylene glycol (PPG) were melted entirely in the mixer after 15 to 20 minutes of processing. This behavior indicates that the torque will decrease when another material

is mixed with PLA, even though the processing time differs. The significance of torque analysis reveals that PEC can help process PLA, especially for mechanical processing such as extrusion to produce filament for 3D printing applications.

Thermogravimetric Analysis (TGA)

The thermogravimetric analysis (TGA) curves for PEC/PLA blends are shown in Figure 3, and the thermogravimetric data for all samples are listed in Table 1. Table 1 shows the temperature at 5 wt% weight loss (T_{d5}) and the maximum decomposition temperature (T_{max}) of the PLA/PEC blends. The 5 wt% weight loss (T_{d5}) of the PLA/PEC blends was decreased with the added PEC. However, adding 6 wt% PEC to the PLA shows an insignificant decrease of T_{d5} from 244.39°C, showing by PLA98/PEC2, to 238.29°C showing by PLA94/PEC6, which is only 6°C. It is probably due to the PLA94/PEC6 blend that maintains stability with the added 6 wt% PEC. The thermal stability of PLA is insignificantly affected by the addition of 6 wt% PEC. PEC shows lower thermal stability than PLA; therefore, the blends with a higher PLA content, PLA98/PEC2, show better thermal stability. Contrary to Wacharawichanant et al. (2019), it is reported that the addition of polyethylene co-polymer content to PLA could not enhance thermal stability. Even though the degradation temperature of polyethylene co-polymer shows a higher value of around 429.48°C, while PLA is at 337.82°C, when polyethylene co-polymer was added to PLA, the degradation temperature of this blend was found to be lower than PLA and polyethylene co-polymer which was 334.26°C. However, the increase of PEC content in the blends makes the sample degrade faster (Figure 3), and PLA90/PEC10 was the fastest to degrade at 500°C compared to others blends fully. Similar results have been reported by Ramlee and Tominaga (2018), the addition of 10%, 30%, 70%, and 90% of PEC to PLA reducing the temperature 5% weight loss (T_{d5}) with the T_{d5} for pure PLA and PEC was 294°C and 198°C, respectively.

The maximum decomposition temperature (T_{max}) obtained from derivative weight loss (DTG) diagrams was used to determine the thermal stability of the PLA/PEC blends. The decomposition temperature is the temperature at which the maximum rate of weight loss occurs (Yayshahri et al., 2019). According to Ramlee and Tominaga (2018), PLA can improve the thermal stability of the PEC. PLA98/PEC2 and PLA96/PEC4 have only one value for T_{max}, indicating that PLA decomposes in a single step, with decomposition temperatures of 364.83°C and 364.87°C, respectively. Adding 2% and 4% of PEC to PLA shows no separated degradation since the difference between PEC and PLA degradation was insignificant. According to Table 1, with the addition of 6 wt% of PEC composition, the PLA and PEC start to decompose separately, causing the degradation of PEC to occur at a lower temperature than the one showed by PLA92/PEC8 and PLA94/PEC6, which around 320°C to 330°C.
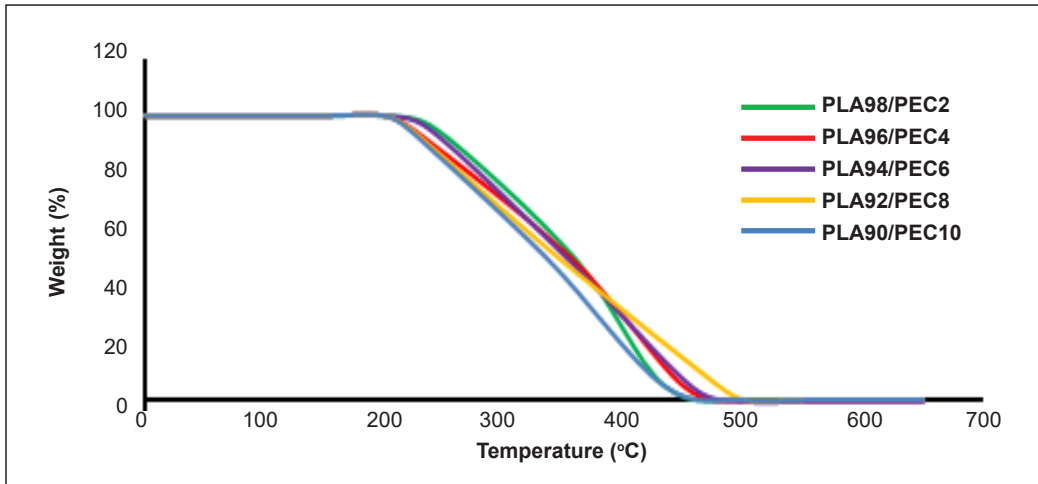
Figure 3. TGA curves for PLA/PEC blends

Table 1
*Thermogravimetric data for PLA/PEC blends*

Sample	T_{d5} [°C]	T_{max} of PEC [°C]	T_{max} of PLA [°C]
PLA98/PEC2	244.39	364.83	364.83
PLA96/PEC4	224.39	364.87	364.87
PLA94/PEC6	238.29	330	364.53
PLA92/PEC8	222.47	320	362.80
PLA90/PEC10	220.64	331.69	370

## Differential Scanning Calorimetry (DSC) Analysis

Using Differential Scanning Calorimetry (DSC), the glass transition temperature (T_g), degree of crystallinity of PLA, and melting temperature (T_m) of PLA/PEC blends made by the melt blending process were determined. The observed value of T_g is usually explained by the strong molecular chain mobility of polymers above T_g and the significantly reduced chain mobility of polymers below T_g (Ramlee & Tominaga, 2018). As in the characterization section, the degree of crystallinity (X_c) is computed using Equation 1. Table 2 shows the DSC data for PLA/PEC blends, Figure 4a indicates the DSC curve of the blend, and Figure 4b shows the melting temperature curve of the blend. The red circle allocated at the curve in Figure 4b refers to the melting temperature peak for each blend. Table 2 and Figure 4b show that when PEC is added to PLA, the melting temperature of the PLA/PEC blends does not vary significantly. Ramlee and Tominaga (2019b) also reported that for the melt-quenched PEC/PLA technique, the melting temperature of PLA crystals is unaffected by the presence of PEC. Other than that, according to Sonseca et al. (2020), T_m values were not showing any significant difference for PLA/OLA blends, where OLA stands for lactic

acid oligomer with the addition of chitosan-based silver nanoparticles (AgCH-NPs). The result for melting temperature obtained by Tao et al. (2017) shows the melting temperature was 167°C for both PLA filament and the composite of WF/PLA can clarify that adding any materials to pure PLA will not cause any different changes in melting temperature of the blends.

The glass transition temperature of a composite is determined by its molecular properties, composition, and compatibility (Tao et al., 2017). According to Table 2, adding 6%, 8% and 10% of PEC decreased T_g values for PLA from 59°C to 56°C. Adding PEC from 6% to 10% leads to this reduction related to macromolecule polymer with high mobility due to an increase in the matrix's free volume (Sonseca et al., 2020). The increase of T_{g1} from 15°C
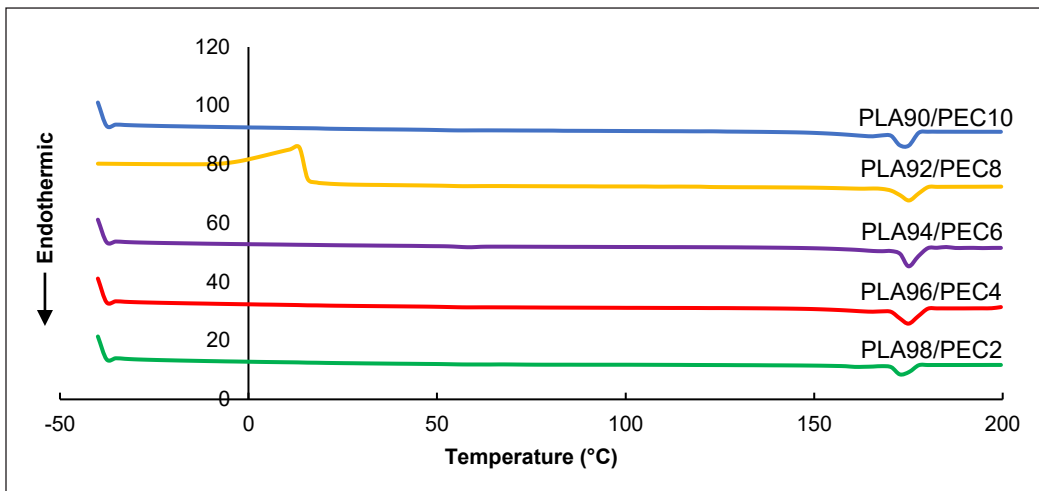
(a)
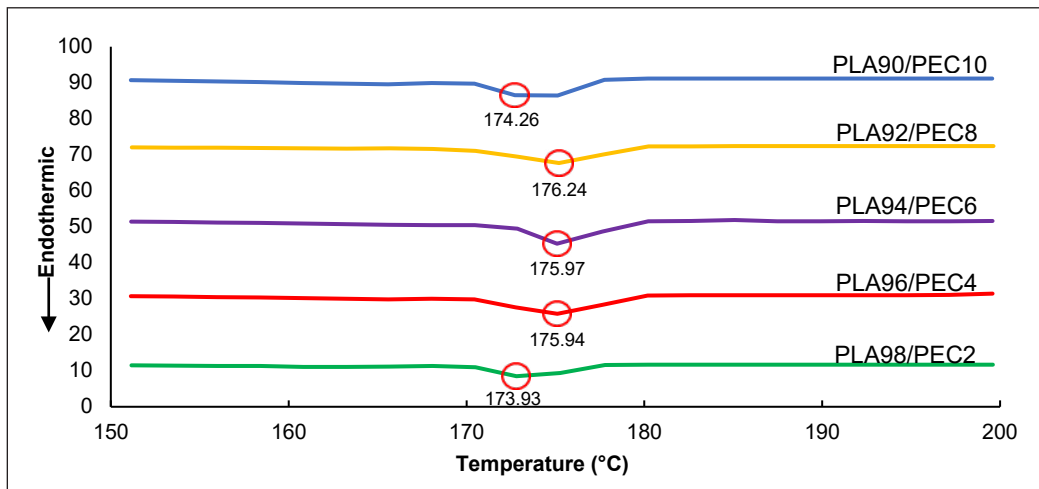
(b)

Figure 4. (a) DSC curves for PLA/PEC blends; (b) DSC melting temperature curves for PLA/PEC blends

Table 2
DSC data for PLA/PEC blends

Sample	Tg_1 (PEC) [°C]	Tg_2 (PLA) [°C]	T_m [°C]	ΔH_m [J/g]	X_c [%]
PLA98/PEC2	15	56	173.93	14.16	**13.50**
PLA96/PEC4	16	58	175.94	42.78	**41.65**
PLA94/PEC6	15	59	175.97	40.59	**40.36**
PLA92/PEC8	16	56	176.24	28.8	**29.26**
PLA90/PEC10	18	56	174.26	47	**48.81**

to 18°C and T_{g2} value from 59°C to 56°C for 6 wt% to 10 wt % PEC shows that PLA/PEC blends are partially miscible, which may be due to the intermolecular interaction between the carbonyl oxygen of PEC and PLA system (Ramlee & Tominaga, 2018). At high PLA content, the presence of PLA in the PEC matrix may act as a barrier to the polymer chains' mobility, increasing the T_{g2} value. Furthermore, with the addition of PEC, the crystallinity of PLA/PEC blends increases, as shown in Table 2. Interestingly, only 4 wt% PEC increased the crystallinity to 41.65%, giving the highest crystallinity of 48.81% with 10 wt% PEC. Similar results were obtained by Ramlee and Tominaga (2018), who stated that the crystallinity of PLA90/PEC10 was 42%. It is due to the flexible PEC in the blends, which improves the polymer's chain mobility (Ramlee & Tominaga, 2018; 2019b). Therefore, the crystallinity of PLA increased with the addition of PEC into the PLA matrix.

Fourier Transform Infra-Red (FTIR) Analysis

Fourier Transform Infra-Red (FTIR) analysis observed the interaction between PLA and PEC in the blend samples. Figure 5 displays the infrared spectrum for the carbonyl group for PLA/PEC film blends, and Figure 6 shows the FTIR curve of the ether group for the blends. The different wavenumbers at each peak are related to the carbonyl groups, including (–C=O) and ether groups (–O–C–O). As illustrated in Figure 5, the extended vibrational mode of the (–C=O) group in the 1700-1800 cm⁻¹ was visible. Line a indicates the value of neat PLA, which is 1754 cm⁻¹ (Chen et al., 2005), and 1738 cm⁻¹, indicated by Line b, where the peak of neat PEC appeared in the infrared spectrum (Ma et al., 2006). Figure 5 illustrates that the absorbance peaks for PLA/PEC blends are between lines a and b, indicated by the arrow for each blend. It is observed that both PLA90/PEC10 and PLA92/PEC8 have a peak at 1752 cm⁻¹. PLA94/PEC6, PLA96/PEC4, and PLA98/PEC2 recorded the same peak value for the carbonyl group, 1753 cm⁻¹. Due to the low loading of PEC content to PLA, the absorbance peak of PLA/PEC blends for the carbonyl group tends to shift towards a neat PLA peak.

Similar research on poly(ethylene carbonate) (PEC) blends with PLA also being observed by Ramlee and Tominaga (2018), and it showed similar carbonyl peak shifts of

the (–C=O) group. Other than that, a similar result for carbonyl peaks was also obtained by Ma et al. (2006) in their study of blending between PLA and poly(propylene carbonate) (PPC). Line c in Figure 6 indicates the value for the (–O–C–O) group in PEC, which is 1207 cm⁻¹ (Ramlee & Tominaga, 2018). The peaks between Line a and Line b show the active peaks compared to others, proving that the molecular interaction bonding of both polymers for PLA and PEC occurred at this point. Furthermore, it can be supported by
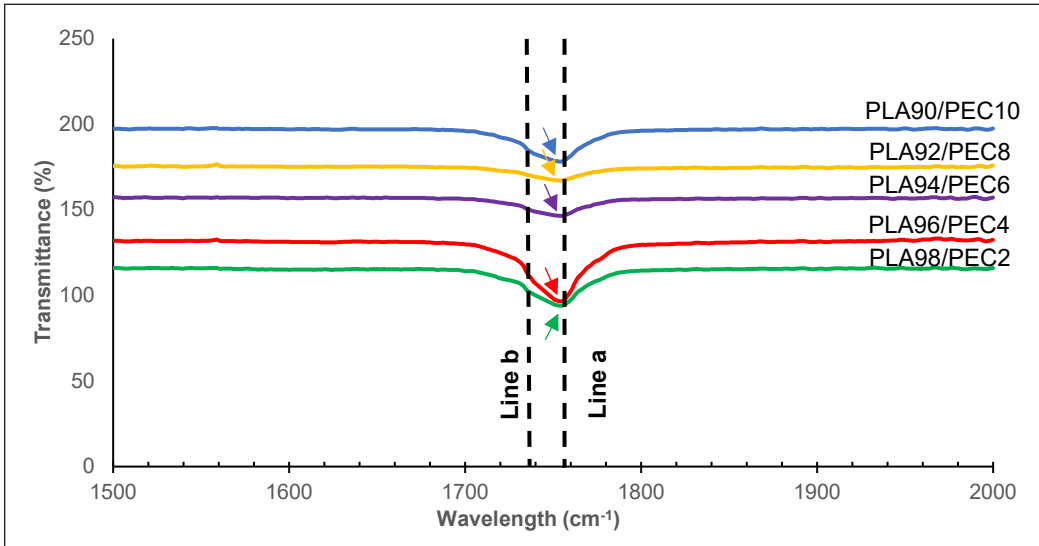

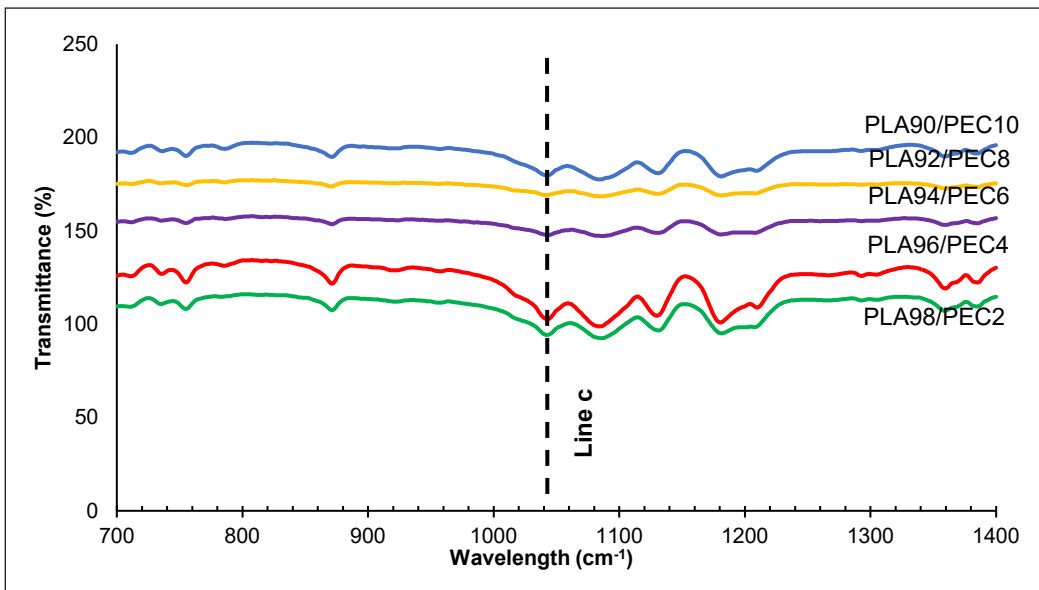*Figure 5.* FTIR curves for the carbonyl group

Figure 6. FTIR curves for ether group

observing Line c, which is the absorbance of the (–O–C–O) ether group. Line c shows a slight shift for all the blends, confirming that molecular interaction occurred between PLA and PEC. Figure 7 depicts the structural image of PLA and PEC interactions for –O–C in –O–C=O of PLA and carbonyl –C=O of PEC. As a result, there is an interaction between the PLA and PEC since it showed a significant change in the absorbance peak when the low ratio range of PEC was added to the PLA/PEC blends.
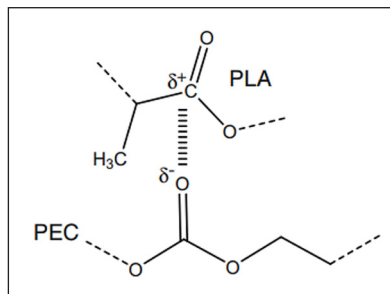

Figure 7. Structural image of interactions between PLA and PEC (Ramlee & Tominaga, 2018)

Mechanical Properties

Figure 8 shows the Young's Modulus values at different compositions of PEC in the PLA matrix. The mechanical parameters of PLA/PEC blends, such as Young's Modulus, tensile strength, and elongation at break, are shown in Table 3. Furthermore, Figure 9 shows the stress-strain (S-S) curve for PLA/PEC blends, and the tensile strength and elongation at break curves for each blend of film samples are shown in Figure 10. The Young's Modulus does not clearly depend on the low PEC content, although the tensile strength and elongation at break do.

According to Ramlee and Tominaga (2019a), it exhibits normal brittle behavior when tensile deformation is applied to neat PLA. In contrast, in its natural form, PEC has a normal ductile stress-strain profile and can endure elongation of more than 400% without rupturing. From Table 3, PLA92/PEC8 recorded the highest Young's Modulus value, 1.79 GPa. On the contrary, PLA90/PEC10 recorded the highest value of Young's Modulus and tensile
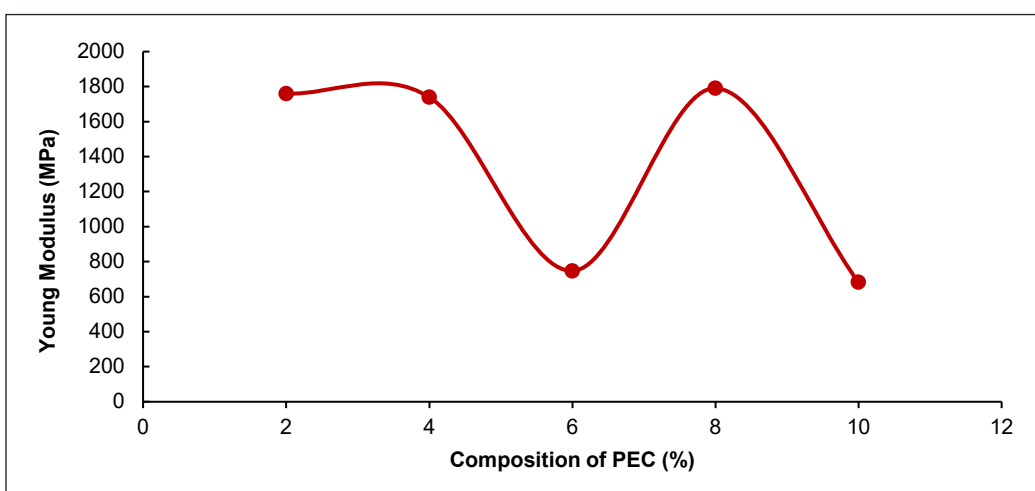

Figure 8. Young's Modulus of PLA/PEC blends for 2, 4, 6, 8, and 10 wt% PEC
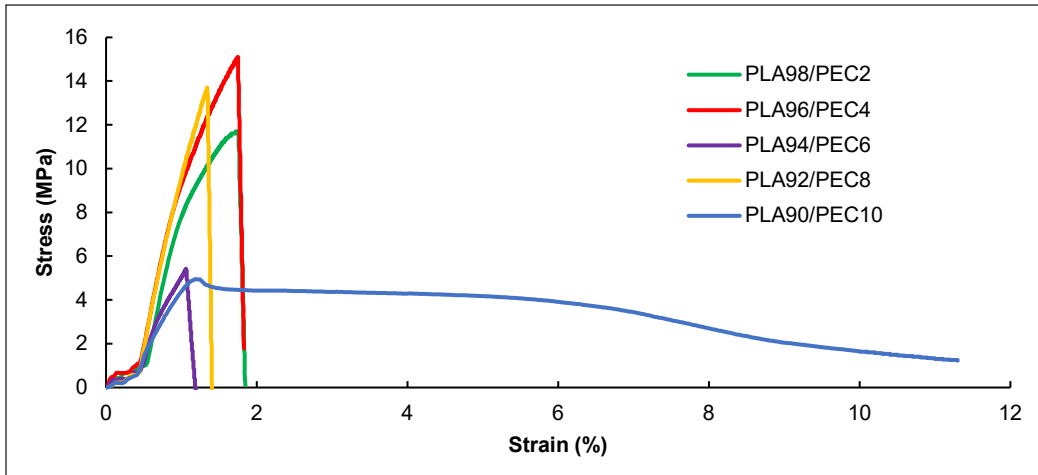
Figure 9. Stress-Strain curve of PLA/PEC blends

strength using the solution casting method reported by Ramlee and Tominaga (2019a). Polymer with high tensile strength and Young's Modulus results in a lower elongation at break value (Hedayati et al., 2020). The elongation at break (ε) of PLA92/PEC8 was 1.34% when the highest value of Young's Modulus was recorded. However, PLA94/PEC6 has the lowest elongation at break, which is 1.06%, but the Young's Modulus (E) and tensile strength (σ) recorded little higher values compared to PLA90/PEC10 blend. It is probably due to the morphology of the film sample, which influences the sample's mechanical characteristics. The lowest value of modulus of toughness (U_t) resulted from PLA94/PEC6, which is 19900 MJ/m^3 due to the lowest value of Young's Modulus, low tensile strength, and low elongation at break. The highest modulus of toughness in this study was recorded by PLA90/PEC10, which is 362000 MJ/m^3. It is shown that the highest composition of PEC will result in the highest modulus of toughness. Similar to Ramlee and Tominaga's (2019b) work, they stated that PEC90/PLA10, which has the highest PEC composition, resulted in the highest modulus of toughness, which is 16.3 MJ/m^3.

The interplay of various elements, including phase morphology, relative modulus of the phases, chain structure, and interfacial adhesion, determines the toughness or breaking energy (Ma et al., 2006). The highest value of toughness is also affected by the blends' crystallinity with increasing crystallinity, resulting in a higher value of toughness. It is due to the intermolecular interaction between PEC and PLA in the blends that resulted in layer structure in the morphology of the blends (Ramlee & Tominaga, 2019a). It is proved from DSC analysis that PLA90/PEC10 has the highest value of crystallinity, which is 48.81 %. Therefore, it results in the highest value of toughness in mechanical properties for this blend. From Figure 8, the tensile strength for PLA/PEC blends with 2 to 8 wt % PEC is above 11.7 MPa, except for PLA94/PEC6, which could not be explained further in this

study. Meanwhile, the tensile strength of PLA has decreased tremendously to 1.23 MPa and reaches the maximum elongation at a break of about 11.3% with 10 wt% PEC, giving the highest modulus of toughness to the PLA/PEC blends. This observation is associated with the result of tensile toughness for PLA/PEC blends prepared by solution casting, in which the PLA toughness was improved from 5.1 MJ/m^3 to 5.5 MJ/m^3 when 10 wt% of PEC was added to the PLA matrix, due to the ductility of PEC that helps in improving the toughness of PLA (Ramlee & Tominaga, 2019a).

Table 3
Mechanical data for PLA/PEC blends

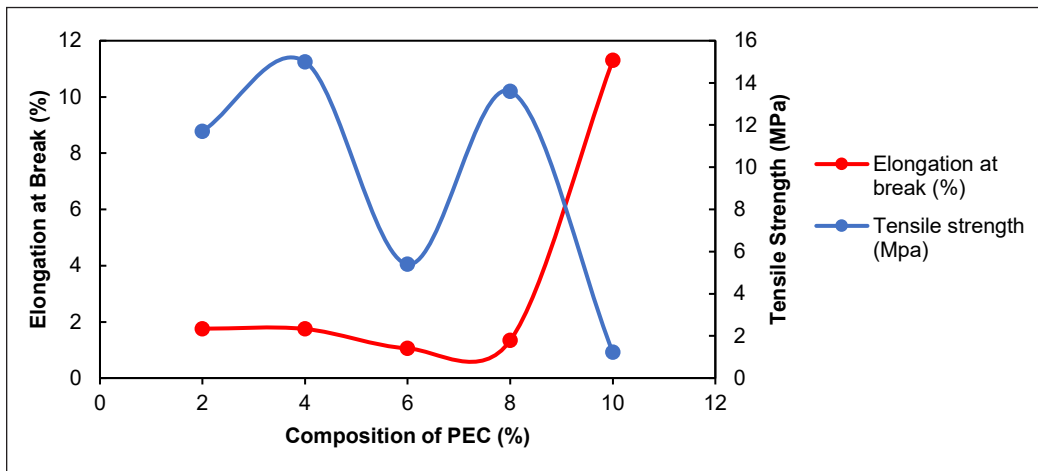| Film Samples	Young's Modulus, E [GPa]	Tensile Strength, σ [MPa]	Elongation at Break, ε [%]	Modulus of Toughness, U_t [MJ/m^3]
PLA98/PEC2	1.76	11.7	1.76	**92100**
PLA96/PEC4	1.74	15	1.75	**115000**
PLA94/PEC6	0.75	5.4	1.06	**19900**
PLA92/PEC8	1.79	13.6	1.34	**63700**
PLA90/PEC10	0.68	1.23	11.3	**362000**

Figure 10. Elongation at break and tensile strength of PLA/PEC blends

CONCLUSION

The blends of PLA/PEC with different PLA and PEC ratios were successfully prepared using the melt blending technique. Despite the different processing times, the torque decreased when PEC was added to PLA. The increasing PEC content in the blends makes the sample degrade faster, as PLA90/PEC10 blends were the fastest to degrade at 500°C compared to other full blends observed in TGA analysis. In addition, 5 wt% weight loss (T_{d5}) of the PLA/PEC blends was decreased with PEC, which influences the thermal stability of

the blends. However, shifting in both T_g for PEC and PLA revealed that the chain mobility induces the crystallinity of PLA that reaches the highest, resulting in 10 wt% PEC, with crystallinity up to 48.81%. The higher toughness value also supports PLA90/PEC10, 362000 MJ/m^3, and high elongation at break 11.3%. Molecular interaction between PEC and PLA blends showed slight changes in the absorbance peaks for the carbonyl group when the low ratio range of PEC was added to the PLA/PEC blends. Adding PEC at more than 6 wt% could ease the melt blending process due to the low torque. However, the blend showed less thermal stability. Nevertheless, it gives a significant toughness property, as shown by PLA90/PEC10 blend. Due to this, low PEC loading is strongly suggested to be an alternative to the PLA modification in various applications such as fused deposition modeling (FDM) in 3D printing and as a compatibilizer.

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