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THERMAL, DYNAMIC MECHANICAL ANALYSIS AND MECHANICAL PROPERTIES OF POLYBUTYLENE TEREPHTHALATE/POLYETHYLENE TEREPHTHALATE BLENDS

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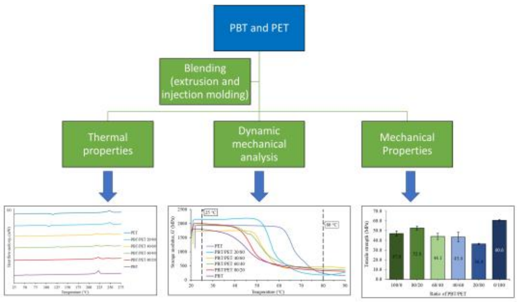
Graphical abstract



Abstract

Differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA) and mechanical tests were conducted to characterize the properties of polybutylene terephthalate/polyethylene terephthalate (PBT/PET) blends. PBT and PET were blended at different PBT/PET ratios (80/20, 60/40, 40/60, 20/80) via twin screw extruder prior to injection molding. DSC characterization showed a single glass transition temperature for all PBT/PET blends indicating that the miscibility occurred in the amorphous region. From DMA results, loss modulus and tan δ also showed a single peak for all PBT/PET blends, confirming the DSC results. At room temperature, PBT/PET 20/80 has the highest storage modulus followed by PBT/PET 80/20 blend. PET has higher tensile strength, flexural strength, Young's and flexural modulus than PBT but lower in elongation at break and impact strength. PBT/PET 80/20 blend has the highest tensile strength, flexural strength, elongation at break, and impact strength compared to other PBT/PET blends. PBT/PET 80/20 blend can be suggested as an optimum formulation with balanced mechanical properties in terms of stiffness and toughness.

Keywords: Polybutylene terephthalate, polyethylene terephthalate, polymer blend, dynamic mechanical analysis, mechanical and thermal properties

Abstrak

Kalorimetri pengimbas pembezaan (DSC), analisis mekanikal dinamik (DMA) dan ujian mekanikal telah dijalankan untuk mengenal pasti sifat-sifat adunan polibutilena tereftalat/polietilena tereftalat (PBT/PET). PBT dan PET telah diadunkan pada nisbah PBT/PET yang berbeza (80/20, 60/40, 40/60, 20/80) dengan menggunakan extruder skru berkembar sebelum diproses menggunakan pengacuan suntikan. Pencirian DSC menunjukkan suhu peralihan kaca tunggal untuk semua adunan PBT/PET menandakan keserasian berlaku di dalam fasa amorfus. Daripada keputusan DMA, modulus kehilangan dan tan δ juga menunjukkan puncak tunggal bagi semua adunan PBT/PET, membuktikan keputusan DSC. Pada suhu bilik, adunan PBT/PET 20/80 mempunyai modulus simpanan tertinggi diikuti oleh adunan PBT/PET 80/20. PET mempunyai kekuatan tegangan, kekuatan lenturan, modulus Young dan lenturan yang lebih tinggi daripada PBT tetapi mempunyai pemanjangan pada kepatahan dan kekuatan hentaman yang lebih rendah. Adunan PBT/PET 80/20 boleh disebut sebagai rumusan yang mempunyai sifat-sifat mekanikal seimbang dari sudut ketegangan dan ketahanan.

Kata kunci: Polibutilena tereftalat, polietilena tereftalat, adunan polimer, analisis mekanikal dinamik, sifat-sifat mekanikal dan termal

1.0 INTRODUCTION

Polymer blends are mixtures of structurally different polymers which adhere together through the action of secondary bond forces, with no covalent bonding between them [1, 2]. It is a method for obtaining desirable property combinations without having to synthesize novel structures [3]. Blending of polymers also provides materials with desired properties at a lower cost, as well as quick formulation changes that will offer manufacturers with plant flexibility and high productivity [3–5] Due to these factors, it has industrial and scientific interest and has become an established technique in the development of new polymeric materials.

Polybutylene terephthalate (PBT) and polyethylene terephthalate (PET) are part of commercially important polymers with applications in various industries such as automotive parts, electrical, electronic, fibers, textile, films, and beverage containers. They have similar thermal and chemical resistance, and mechanical properties, but PBT has slightly better impact strength compared to that of PET. PBT also has a faster rate of crystallization than PET which makes it the preferred material for industrial scale molding [6–8]. Many studies were reported on improving the properties of PBT and PET through incorporation of fillers and blending with other polymers [7–11].

Blending of PBT and PET has attracted the interest of many researchers [2, 12–18]. Avramova reported that PBT/PET blend has an excellent miscibility and intermolecular interaction. They also reported that PBT/PET blend is miscible within the amorphous region as indicated by a single glass transition temperature (T_g) based on the DSC study [2]. Recently, another researcher revealed that the miscibility can occur in both amorphous and crystalline region when the blend is cooled slowly at 2 °C min^{-1} [15]. The miscibility of PBT/PET blends is also influenced by the transesterification reaction that occurred above the melting temperature, producing random block co-polymers that compatibilized PBT and PET [2, 18].

Mechanical properties of PBT/PET blends were studied previously by several researchers [2, 12–14, 17]. Generally, PET has higher tensile and flexural properties than PBT but lower in elongation at break and impact strength. It is shown that tensile strength and Young's modulus of the PBT/PET blends were lower than PET but higher than PBT as reported by Szostak [12]. However, Mishra and Deopura reported that most of the tensile strength of the blends is even much lower than PBT [13]. On the other hand, Aravinthan and Kale showed that equal ratio of PBT/PET blend (50/50 wt.%) has higher tensile strength compared to PBT, PET and other PBT/PET blends. They also reported that the PBT/PET blends exhibit improved impact strength compared to the neat PBT and PET [14].

Dynamic mechanical analysis (DMA) of polymeric materials is governed by their viscoelasticity. Depending on the response to mechanical stimulation, the material can be classified either as elastic (solid phase) or viscous (flowable phase). The elastic and viscous contribution to the DMA behavior of the polymer depends on the temperature and the time scale of the experiment [19]. Loss modulus is the heat dissipation due to the rearrangement or relaxation of the polymer chain that represents the viscous or flowable phase since it is the phase where the polymer chain started to be mobile [19]. Tan δ, also known as loss tangent or damping factor, is the ratio between loss modulus and the storage modulus in which illustrates the material's transition from elastic phase into viscous phase [19].

Several studies have been reported on the mechanical and thermal properties of PBT/PET blends [2, 12–14, 17] although, most of the studies investigated tensile properties with much less on flexural properties and impact strength. This paper reports on the DMA of PBT/PET blends since DMA is a useful method to evaluate the intermolecular interaction between neat PBT and neat PET in the PBT/PET blend. Therefore, DMA can be used to study the miscibility and thermal transitions of PBT/PET blends. It also can be utilized to determine the modulus at different temperatures, thus establishing the optimal working temperature of the material. Taking these factors into account, the thermal, DMA and mechanical properties of PBT/PET blends at different ratios were investigated. The knowledge on the properties of PBT/PET blend at various ratio will be of interest to the industrialist. The PBT/PET blend composition with balanced mechanical properties in terms of stiffness and toughness for applications in automotive, electronic housings and aerospace industries can also be determined.

2.0 METHODOLOGY

2.1 Materials

The materials used in this research were PBT and PET. PBT (grade 1100-211M) was manufactured by Chang Chun Chemical (Jiangsu) Co. Ltd. China, while PET (grade A-PET) was manufactured by Worldwide Resins & Chemicals (Malaysia) Sdn. Bhd.

2.2 Preparation of PBT/PET Blends

The PBT/PET blends were prepared according to the formulations in Table 1.

Table 1 Formulations of PBT/PET blends

Sample Designation	PBT (wt.%)	PET (wt.%)
PBT	100	0
PBT/PET 80/20	80	20
PBT/PET 60/40	60	40
PBT/PET 40/60	40	60
PBT/PET 20/80	20	80
PET	0	100

The resins were dried overnight in an oven at 80 °C and physically mixed before the blending process. The resins were blended by using a Werner & Pfleiderer ZSK25 (Germany) twin screw extruder (L/D = 36) with rotation speed of 40–50 rpm. The resulting extrudates were then passed through a pelletizer and dried again prior to injection molded (JSW 100Ton) into flexural, tensile and impact tests samples. Temperature setting for both instruments was at 260/270/280/285 °C, from the hopper to the die.

2.3 Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) was performed on the Mettler Toledo DSC1 STAR system, according to ASTM D3418, to obtain glass transition temperatures (T_g), crystallization temperatures (T_c), melting temperatures (T_m), and degree of crystallinity (X_c). These values were taken from the first heating thermogram to reflect the effect of processing on the blends since all samples were taken from the same injection molded samples. To calculate X_c, it requires the enthalpy of fusion of 100 % crystalline polymer (ΔH_o). Since there is no known value of ΔH_o of the PBT/PET blends, the X_c of each blend are calculated separately corresponding to PBT and PET individually. The calculation of X_c is presented in Equation 1 [20].

$$X_c = [(\Delta H_m + \Delta H_{cc})/(\Phi \Delta H_o)] \times 100\ \% \qquad \text{Eq. 1}$$

where, ΔH_m is the enthalpy of melting, ΔH_{cc} is the enthalpy of cold crystallization, and Φ is the weight fraction of the polymer in the blend. The values of ΔH_o for PBT and PET are 140 J g^{-1} and 166 J g^{-1} respectively [18, 21]. The samples were weighed about 5-10 mg and sealed in an aluminium pan. The heating and cooling rate were 10 °C min^{-1} within temperature range of 30 to 260 °C. The characterization was conducted under nitrogen atmosphere with flow rate at 50 ml min^{-1}.

2.4 Dynamic Mechanical Analysis

Dynamic mechanical analysis (DMA) was conducted according to ASTM D7028 via a Perkin Elmer DMA equipment at heating rate of 2 °C min^{-1} from 20 to 90 °C. A three-point bend fixture was used at a constant frequency of 1 Hz. Sample dimension of 60 mm × 10 mm × 3 mm was used.

2.5 Mechanical Tests

Tensile and flexural tests were conducted at room temperature according to ASTM D638 and ASTM D790 respectively. Both tensile and flexural samples were tested on a Llyord EZ 20 kN universal tensile machine at crosshead speed of 10 mm min^{-1} and 3 mm min^{-1} respectively.

The Izod impact strength of the standard samples was measured using a standard pendulum type hammer mounted on a Zwick/Roell Izod impact tester, according to ASTM D256. The samples were notched by Zwick/Roell automatic notching machine. For each mechanical test, minimum of five samples per formulation were used and the average value calculated.

3.0 RESULTS AND DISCUSSION

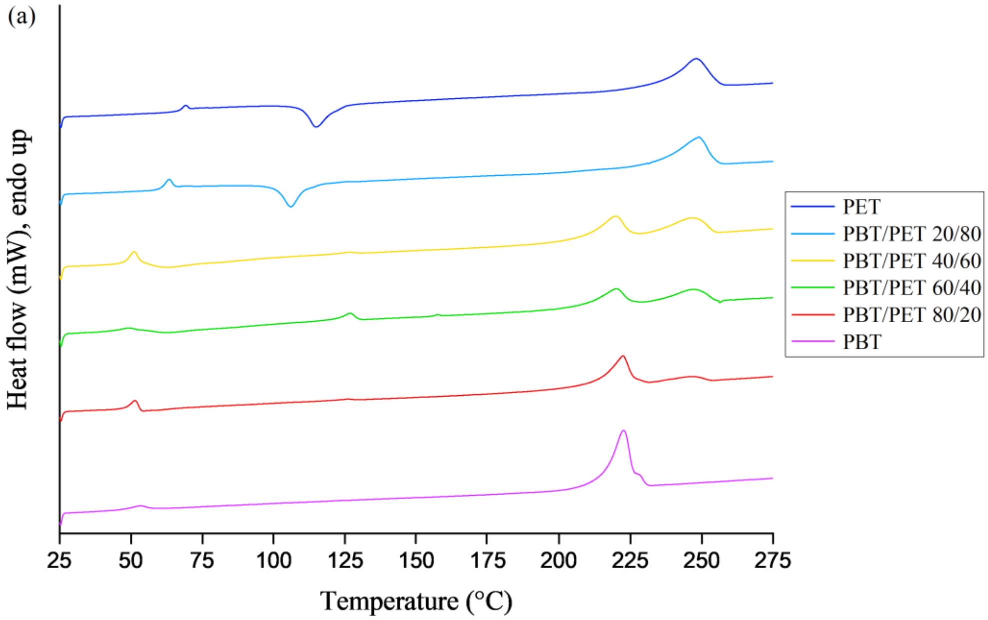
3.1 Differential Scanning Calorimetry

Figure 1(a) and (b) illustrates the first heating and cooling thermograms of PBT, PET and PBT/PET blends and the thermal properties are summarized in Table 2. From the figures, all samples show noticeable glass transition (T_g), crystallization (T_c), and melting temperature (T_m). It can be seen that T_g of PBT is 55 °C which is 14 °C lower than PET and is in agreement with previous studies [2, 14]. This is due to the long and flexible butylene chain of PBT making it less polar and slightly weaker intermolecular interactions compared to PET. Consequently, PBT has slightly better chain mobility compared to PET, thus lower T_g.

A single T_g value is observed for all PBT/PET blends indicating that PBT and PET are miscible in the amorphous region which consistent with DMA results i.e., loss modulus and tan δ. Similar results were also reported by previous researchers [2, 12, 14]. It is observed that increasing the composition of PBT in PBT/PET blend decreased the T_g of the blend which reflect the results from DMA i.e., loss modulus and tan δ. This is due to PBT could improve the chain mobility of the blends. Several researchers also reported similar result where T_g was reduced as the content of PBT increased [2, 14].

PET and PBT/PET 20/80 blend have cold crystallization (T_{cc}) at 115 °C and 106 °C respectively as observed from Figure 1(a), which is consistent with previous research [2, 22]. This shows that PET has low crystallization rate and could not crystallized fully during cooling throughout the injection molding process. From Table 2, it can be seen that PBT/PET 20/80 blend cold-crystallized earlier (at 106 °C) and faster (smaller ΔT_{cc}; 10 °C) than PET. This is probably due to block co-polymer produced by transesterification reaction acted as nucleation sites for PET in the blend to cold-crystallize earlier and faster than pure PET. Other researchers also reported this nucleation effect [12, 23].

From Table 2, PET has higher T_c than PBT which is consistent with previous studies [2, 8]. Poulose *et al*. showed that PET has higher T_c than PBT for both first and second cooling scan [8]. Based on Figure 1(b), all blends have single T_c, despite PBT and PET crystallize separately and exhibit different T_m. This is due to the synergistic effect where the crystallization of PET and PBT is enhanced by each other. This behavior is confirmed by several researchers [2, 12, 14].



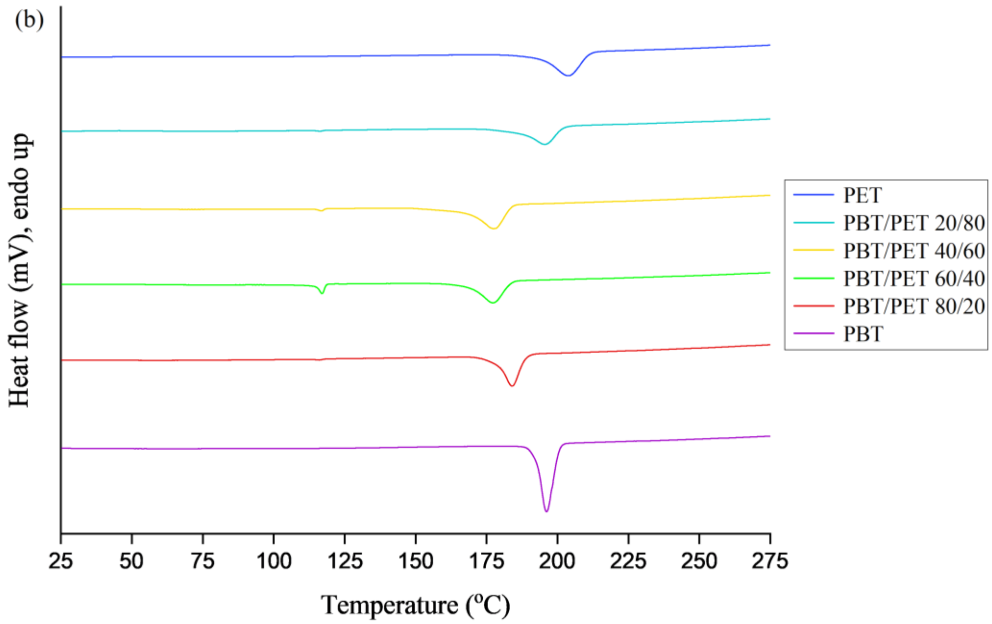


Figure 1 Thermograms of PBT, PET and PBT/PET blends. (a) heating (b) cooling

Table 2 Thermal properties of PET, PBT and their blends

Samples	**T_g (°C)**	**T_{cc} (°C)**	**ΔT_{cc} (°C)**	**T_c (°C)**	**ΔT_c (°C)**	**T_m (°C)**		**X_c (%)**	
						PBT	**PET**	**PBT**	**PET**
PBT	55.1	-	-	196.1	8.0	222.6	-	33.4	-
PBT/PET 80/20	52.7	-	-	184.0	10.2	222.4	245.9	24.7	22.1
PBT/PET 60/40	53.0	-	-	177.3	14.5	219.9	247.5	18.2	28.0
PBT/PET 40/60	53.2	-	-	177.5	14.9	219.7	246.8	31.4	20.5
PBT/PET 20/80	65.2	106.1	10.0	195.6	15.5	-	249.0	-	19.4
PET	67.8	115.0	12.3	203.9	17.2	-	248.1	-	15.9

According to Avramova, the addition of PBT facilitates the crystallization of PET since PBT has high crystallization rate and can act as nucleating agent [2]. Compared to PBT and PET, the T_c of PBT/PET blends shifts to low temperature indicating that crystallization was affected by transesterification reaction. The block co-polymer improved the chain mobility of the blend (as evidenced by low T_g of the blends) making it difficult for the chain to rearrange at high temperature thus, the crystallization occurred at low temperature.

ΔT_c are the difference between onset and end of T_c curve, in which indirectly indicates the crystallization rate of polymer. Small ΔT_c value indicates high crystallization rate since shorter time taken for the polymer to crystallize fully. From Table 2, PBT shown a small ΔT_c which is about 114 % lower than PET and further proved that PBT exhibit high crystallization rate and low crystallization rate for PET. It is also worth noting that ΔT_c decreasing with increasing PBT content. This confirms that PBT facilitates the crystallization of the PET as reported previously [2].

From Figure 1(a), T_m of PET (248.1 °C) is higher compared to PBT (222.6 °C) which is similar to previously reported studies [2, 12]. PBT displays one main melting peak with a small shoulder at around 227 °C. This is due to the existence of two different types of crystals corresponding to the original and recrystallized crystals, being the latter is the main peak [24 – 26].

It is worth noting that double T_m peaks were observed for all blends except PBT/PET 20/80 blends. This implies that PBT/PET 80/20, 60/40 and 40/60 blends are not miscible in the crystalline region and crystallized separately. Similar behavior was also reported by other researchers [2, 12, 14]. In case of PBT/PET 20/80 blends, one T_m peak appeared corresponding to PET (absent of PBT peak) probably due to PBT content was low. Other researcher also reported similar result where PBT/PET 20/80 blend has single T_m peak [14].

Compared to PET, PBT exhibit higher X_c by 110 % due to high crystallization rate of PBT. Significant increase in X_c can be observed for PET fraction in the blends with the addition of PBT, which is even higher than pure PET up to 76 %. At the same time, the crystallinity of PBT fraction is decreasing with decreasing PBT content. A possible reason for this behavior is that PBT content was already reduced in the blends and PBT facilitated the crystallization of PET. Similar behavior was supported by several other researchers [2, 14, 17].

It is also observed that there is a small endothermic peak (Figure 1(a)) at around 125 °C for PBT/PET 60/40 and 40/60 during heating and a small exothermic peak (Figure 1(b)) appeared during cooling slightly below 125 °C. These peaks appearance could be corresponding to the block co-polymer produced during processing through transesterification reaction. This is due to the almost equal amount of PBT and PET, increasing the probability of the transesterification reaction to occur and produce long enough block co-polymer that can crystallize [27]. On the other hand, PBT/PET 80/20 and 20/80 do not show any of these peaks probably due to the small amount of either PBT or PET to produce enough block co-polymer. Kim *et al*. (2001) reported that small amount of either PBT or PET will produce low molecular weight block co-polymer [27].

3.2 Dynamic Mechanical Analysis

The DMA behaviors of PBT/PET blends are illustrated in Figure 2, 3 and 4 and summarized in Table 3. Since both DMA and flexural test are using three-point bending method, the flexural modulus of the blends is also included in Table 3 for comparison.

Figure 2 shows the storage modulus of PBT/PET blends at different PBT and PET ratios. At room temperature (25 °C), storage modulus of PET is about 9 % higher than PBT due to the lower chain mobility of PET resulting in a more rigid structure. It can be seen that at that temperature, both PBT/PET 80/20 and PBT/PET 20/80 blends have higher storage modulus than the neat PBT and PET. PBT/PET 20/80 blend has higher storage modulus values than neat PET due to higher crystallinity content. The crystalline phase can act as a reinforcement which restricts the chain mobility of the polymer matrix. The storage modulus of PBT and PET at room temperature is almost similar in values to flexural modulus. The flexural modulus for PBT and PET are 1777 and 2151 MPa respectively, while the storage modulus for PBT and PET are 1795 and 1953 MPa respectively.

It is also observed that the transition step of PBT occurred much earlier than PET which is consistent with their T_g. Similar observations were reported by several researchers [17, 28, 29]. The storage modulus of PET remained constant from room temperature until approximately 60 °C where the storage modulus undergone a sharp drop at the T_g transition temperature. However, no such plateau can be observed in the case of PBT. Plateau regions can also be observed for all the blends, although not as long as the neat PET. This shows the effectiveness of PET in enhancing the thermal stability of PBT and the transition in storage modulus occurs at higher temperatures.

At around 80 °C, all neat polymers and polymer blends are in the rubbery state where the polymer chains have enough energy to untangle and becomes mobile, leaving the crystalline phase to provide the mechanical strength [17]. It is seen that PBT has a higher storage modulus (439 MPa) than PET (242 MPa) at this temperature further confirming that PBT has higher crystallinity than PET. PBT/PET 80/20, 60/40 and 40/60 blends also have higher storage modulus than PET demonstrating that the addition of PBT into the blends increased the stiffness of PET due to the increase in crystalline phase.

Loss modulus of the PBT/PET blends is shown in Figure 3. From the figure, it can be observed that PET has the peak temperature of 68 °C while PBT has the peak temperature of 47 °C. Peak temperature of loss modulus is associated with T_g, and this result is consistent with the T_g from previous studies [17, 28, 29]. It is also interesting to note all PBT/PET blends show a single peak indicating that the PBT and PET is completely miscible in the amorphous region. This behavior is consistent with the T_g from DSC characterization later in this discussion.

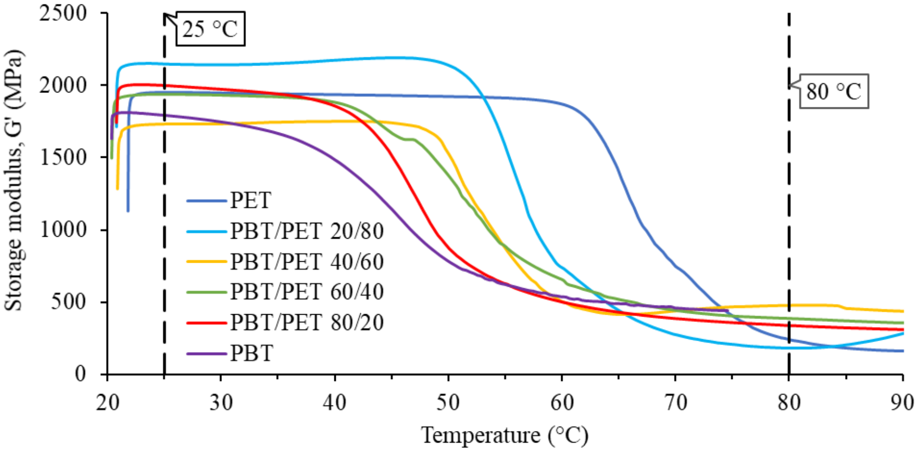


Figure 2 Storage modulus of PBT/PET blends

Table 3 DMA results of PBT, PET and PBT/PET blends

Samples	Storage Modulus at 25 °C (MPa)	Storage Modulus at 80 °C (MPa)	Flexural Modulus (MPa)	Loss Modulus at peak (°C)	Tan δ at peak (°C)	Tan δ values at peak
PBT	1795	439*	1777	46.6	53.9	0.16
PBT/PET 80/20	1999	340	2060	50.4	52.9	0.24
PBT/PET 60/40	1941	388	1938	53.4	57.6	0.30
PBT/PET 40/60	1735	478	2133	52.0	58.7	0.34
PBT/PET 20/80	2151	183	2434	58.4	64.8	0.36
PET	1953	242	2151	67.8	75.0	0.42

*value at 75 °C.

It is noted that at room temperature (25 °C), the loss modulus values of PBT is higher than PET. These results are consistent with the impact test results where PBT has a higher impact strength than PET at room temperature. Figure 3 also shows that the peak loss modulus of PET is much higher than PBT, due to higher chain mobility at the T_g for PET compared to PBT. The reason is that PET with lower crystallinity than PBT will have less crystalline regions that restrict chain mobility at around T_g. For the PBT/PET blends, the relationship between crystallinity and peak values can also be observed where the higher the crystallinity, the lower is the peak values. This relation is also reported in a study previously [28].

Figure 4 presents the variation tan δ with temperature for neat PET, neat PBT and PBT/PET blends. The peak of tan δ can be used to determine the T_g. As seen from the figure, the temperature for peak tan δ of PBT is at 54 °C, which is lower than PET which is 75 °C. The higher T_g value of PET compared PBT is consistent with previous findings [17, 28, 29]. Similar to DSC, the peak temperature of tan δ also consists of single peak for each PBT/PET blend indicating that PBT and PET are miscible in the amorphous region. The tan δ or T_g of the PBT/PET blends were increased with increasing PET content in the blend, consistent with the trend in loss modulus. This is because PET has less crystallinity than PBT and at T_g, the PET chains are more mobile due to less hindrance from the crystalline phase.

3.3 Mechanical Properties

Three mechanical tests, including tensile, flexural and impact tests, were carried out to investigate the mechanical properties of PBT/PET blends and the acquired data of mechanical properties were analyzed with one-way ANOVA. Figure 5 shows the tensile strength of PBT, PET and PBT/PET blends at different ratios. From the figure, it can be seen that the tensile strength of PET is 29 % higher than PBT. The reason PBT has lower tensile strength than PET is the longer butylene chain in PBT making it more flexible [15]. This is consistent with a previous study whereby the tensile strength of PET is higher than PBT, but at a much lower value of only around 2 % [12].

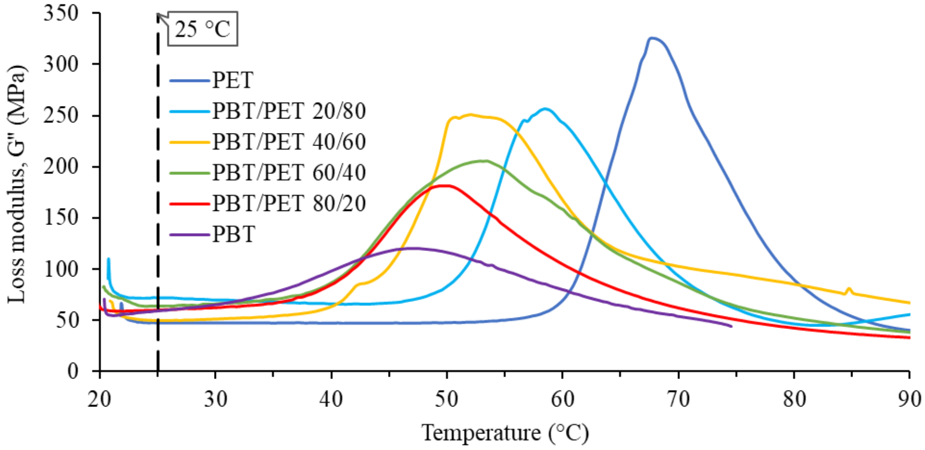


Figure 3 Loss modulus of PBT/PET blends

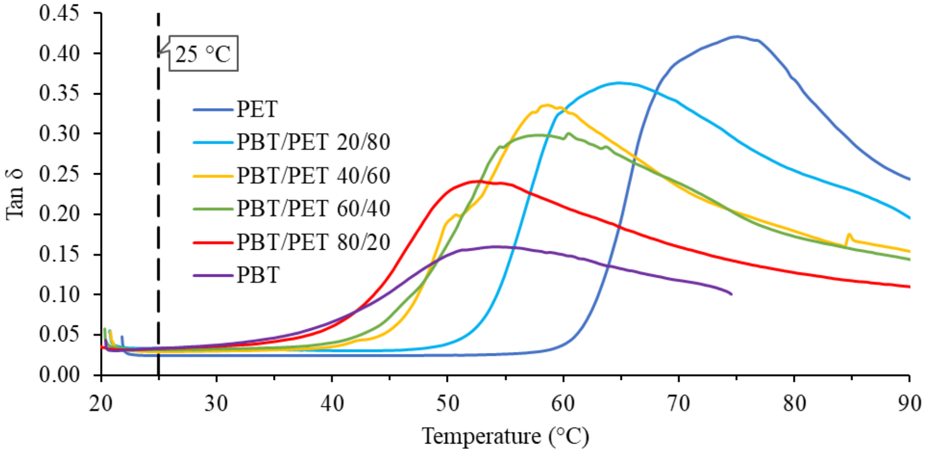


Figure 4 Tan δ of PBT/PET blends

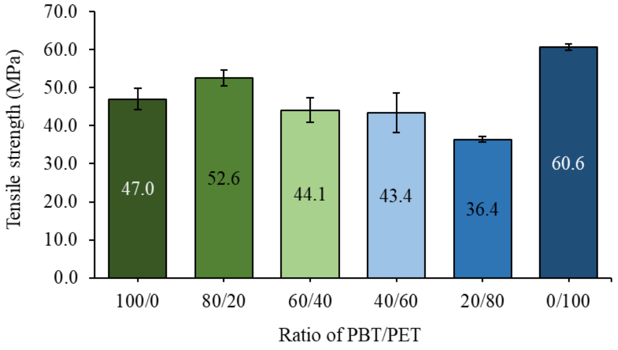


Figure 5 Tensile strength of PBT, PET, and PBT/PET blends

It is also noted that tensile strength of the PBT/PET blends are lower than that of PBT with the exception of PBT/PET 80/20 which is 12 % higher than PBT. One-way ANOVA analysis revealed that there is no significant difference between PBT/PET blends from 100/0 to 40/60 in terms of their average tensile strength (p>0.05). However, PBT/PET 80/20 exhibited a significantly higher average tensile strength compared to other formulations. This is interesting because with only 20% addition of PET, the tensile strength has increased from 47 to 53 MPa. However, the tensile strength values of PBT/PET blends decrease with increasing PET due to the phase separation in the crystalline state resulting in incompatibility. This is being supported by previous studies which reported that the phase separation occurred in crystalline state when PBT content is in between 10 to 40 wt.% [12, 13].

The Young's modulus of PBT, PET and their blends are presented in Figure 6. The Young's modulus of PET is about 20 % higher than PBT because of the rigid nature of PET as explained earlier. This is consistent with a previous study in which PET was reported to be approximately 70% higher than PBT [13]. It is also worth noting that the Young's modulus of the blends increased with increasing PET contents where PBT/PET 20/80 blend is the highest among the blends. The increase of Young's Modulus with increasing PET content is similar to a previously reported study [13]. Similar to the tensile strength, one-way ANOVA analysis verified the insignificant difference between PBT/PET blends from 100/0 to 40/60 in terms of their average Young's modulus (p>0.05).

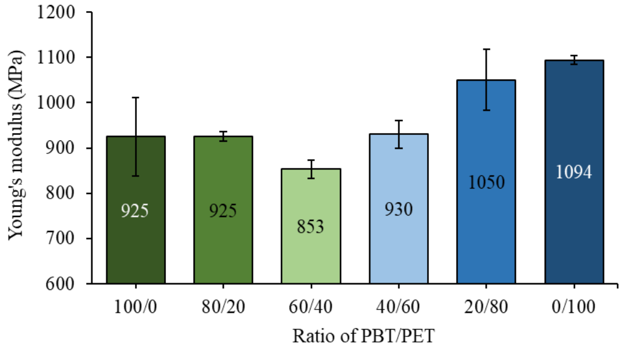


Figure 6 Young's modulus of PBT, PET and PBT/PET blends

Elongation at break of PBT, PET and PBT/PET blends is illustrated in Figure 7. From the figure, PBT has the longest elongation at break compared to PET and the blends by 2-8 folds. This is most probably due to the entanglement of long chain of PBT unraveled itself when load at low strain rate is applied. It can be seen that the elongation of the blends decreased with increasing PET content where PBT/PET 80/20 blend is the highest among the blends. This shows that the elongation at break of the blends is greatly affected by the content of PET. Besides that, high elongation at break indicates that the area below strain-stress curve is large. This implies that the PBT/PET 80/20 blend and PBT are able to absorb a lot of energy and as a result, the two formulations are expected to have high impact strength.

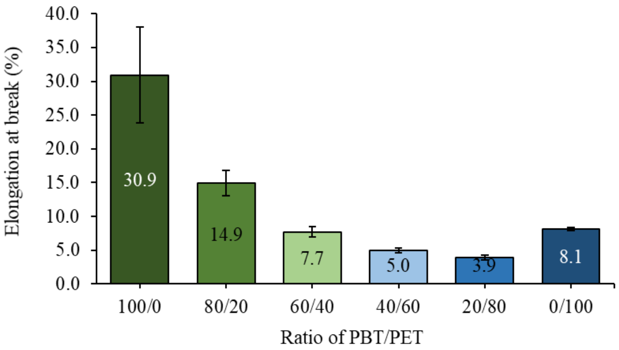


Figure 7 Elongation at break of PBT, PET and their blends

As shown in Figure 8, flexural strength of PBT, PET and their blends exhibited similar trend as tensile strength. Similarly, PET has higher flexural strength (by 38 %) than PBT due to the rigid nature of PET. Another researcher also reported the flexural strength of PET is higher than PBT but only around 1 % difference [2]. It is also noted that the blends have lower flexural strength than PBT with the exception of PBT/PET 80/20 blend which displays the highest value compared to the blends. This is probably due to the same factor as discussed in tensile strength section which is phase separation due to different stage of crystallinity.

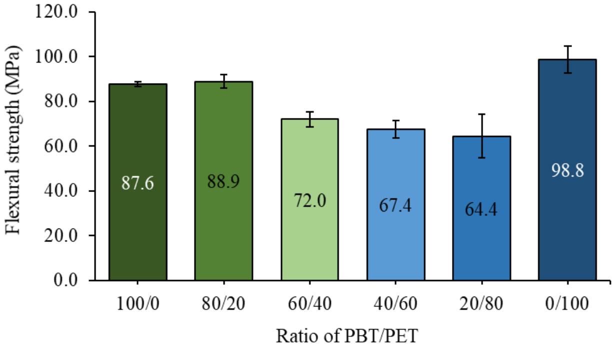


Figure 8 Flexural strength of PBT, PET and their blends

Flexural modulus (Figure 9) also exhibits similar trend as Young's modulus where PET display a higher flexural modulus than PBT by 21 %, and the flexural modulus increased with increasing PET content. This observation is consistent with storage modulus and similar observation was reported by another study [14]. Unlike Young's modulus, the flexural modulus of the blends is much higher than PBT, where PBT/PET 20/80 blend has the highest flexural modulus compared to other blends and even exceeded PET by 13 %. As PET content increased, the flexural modulus also increased which is due to the rigid nature of PET that restrict the chain mobility thus, increased the flexural modulus. These results are also in agreement with storage modulus.

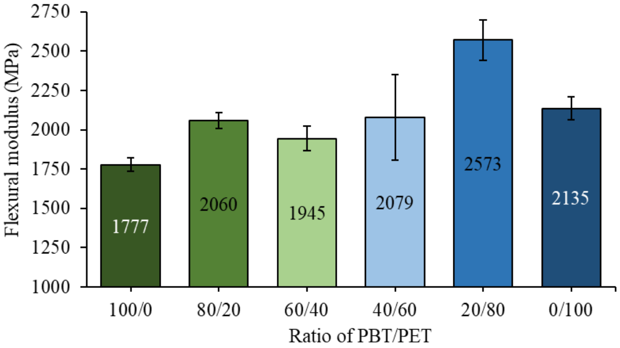


Figure 9 Flexural modulus of PBT, PET and PBT/PET blends

The impact strength of PET, PBT and their blends is presented in Figure 10. As expected, PBT has the highest impact strength and 25 % higher impact strength than PET due to the long and flexible butylene chain within PBT in which enabling it to absorb the impact energy. Similar results were reported by other researchers [12, 14]. It can be seen that PBT/PET 80/20 blend has the highest impact strength compared to other blends and 16 % higher than PET. As PET content increased up to 80 wt.%, the impact strength of the blends decreased because of the ability of the blends to absorb impact energy decreases with decreasing PBT content. These results are in agreement with elongation at break, loss modulus and tan δ results discussed earlier in which proved that PBT able to absorb a lot of energy before breaking.

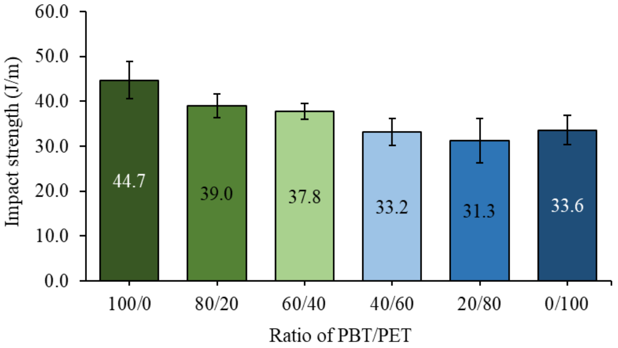


Figure 10 Impact strength of PBT, PET and PBT/PET blends

Stiffness and toughness are two important properties for structural applications. Stiffness is important for load supporting function while toughness offers durability. Figure 11(a)-(b) illustrates the properties of PBT/PET blend in terms of stiffness (Young's and flexural modulus) and toughness (impact strength). From Figure 11(a), it can be seen that PET, PBT/PET 20/80 and 40/60 blends have good stiffness but not as durable as PBT. On the other hand, PBT/PET 80/20 and 60/40 blends have good durability but PBT/PET 60/40 has the lowest stiffness. Similarly, based on Figure 11(b), PET, PBT/PET 20/80 and 40/60 blends have good stiffness but quite brittle. PBT/PET 80/20 and 60/40 blends have good durability and better stiffness than PBT. It can be concluded that PBT/PET 80/20 blend, with Young's modulus of 925 MPa, flexural modulus of 2060 MPa and impact strength of 39.0 J m^{-1}, has good balanced mechanical properties in terms of stiffness and toughness.

4.0 CONCLUSION

PBT/PET blends were produced by melt blending PBT and PET at different ratios via twin screw extruder followed by injection molding into test samples. DSC confirmed the miscibility of the PBT/PET blends. The miscibility appeared as single T_g and double T_m peaks in the DSC thermogram, indicating the miscibility only occurred in the amorphous region not in the crystalline region. Single T_c peak was obtained for all blends demonstrating that there is synergistic effect where the crystallization of PBT and PET is enhanced by each other. Based on the X_c of the blends, PBT was found to significantly increase the X_c of PET. From the DMA, loss modulus and tan δ showed a single peak for all PBT/PET blends indicating that the blends are miscible in amorphous region confirming the DSC results. The T_g of the PBT/PET blends are between the T_g of PET and PBT. The tan δ and loss modulus peak values increased with increasing PET because PET has less crystallinity than PBT. PET maintain its storage modulus from room temperature until around 60 °C, after which it decreased sharply. PBT/PET 20/80 blend has the highest storage modulus followed by PBT/PET 20/80. PET has higher tensile strength, flexural strength, Young's and flexural modulus than PBT but lower in elongation at break and impact strength. PBT/PET 80/20 blend has the highest tensile strength, flexural strength, elongation at break, and impact strength compared to other PBT/PET blends. On the other hand, PBT/PET 20/80 blend has the highest Young's and flexural modulus among the PBT/PET blends. PBT/PET 80/20 blend showed the best well balanced mechanical properties in terms of stiffness and toughness.

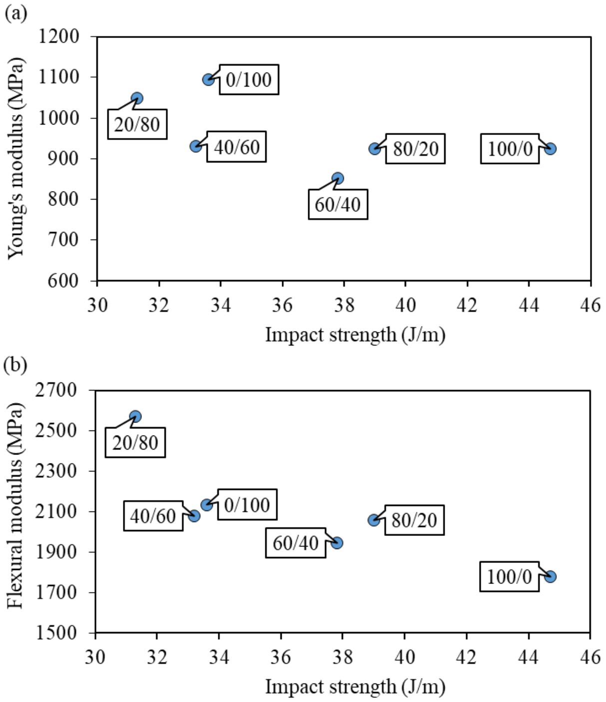


Figure 11 Properties of PBT, PET and PBT/PET blends in terms of stiffness and toughness (a) Young's modulus and impact strength (b) flexural modulus and impact strength

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