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Structure-Property Correlation in PTT/PP Blends with Improved Mechanical Performance

Shrikant Deo[1], Swamini Chopra[2,*], Kavita Pande[3], J. D. Ekhe[4], Dilip Peshwe[5]

Abstract

The present work investigates a series of poly (trimethylene terephthalate) (PTT)/polypropylene (PP) blends prepared with varying PP concentrations in order to improve the overall performance of PTT, particularly with respect to mechanical properties and processability. PTT is a promising engineering thermoplastic owing to its balanced stiffness, resilience, and chemical resistance; however, its relatively high cost and processing limitations often restrict its wider application. In this context, blending with PP offers a practical and economical route to tailor its properties and extend its application potential. A systematic study of the prepared PTT/PP blends demonstrates that the incorporation of PP significantly influences the performance of the base polymer. Mechanical characterization (Tensile, Impact and hardness) reveals that the blends exhibit improved properties compared with neat PTT, indicating that the addition of PP contributes positively to the strength–performance balance of the material. Thermal and structural investigations using Differential Scanning Calorimetry (DSC) and X-ray Diffraction (XRD) confirm that the fundamental structural integrity and crystalline characteristics of PTT remain substantially preserved after blending with PP. This suggests that the incorporation of PP does not adversely disturb the essential structural framework of the PTT matrix. Furthermore, the Melt Flow Index (MFI) analysis showed that the PTT/PP blends flow more easily than pure PTT, indicating improved processability and easier fabrication by conventional processing methods. The results also suggest that the interaction between PTT and PP is not merely a simple physical mixing phenomenon; rather, a degree of synergistic interaction exists between the two polymers, contributing to the observed property enhancement. Overall, the study establishes that the addition of small amounts of PP, particularly in the range of 5–10 wt.%, is beneficial for improving both the processing behavior and mechanical performance of PTT, leading to the development of a more versatile and industrial application oriented polymer blend system.

***Author for Correspondence**
Swamini Chopra
E-mail id: chopra.swamini@gmail.com

[1]Research Scholar, Department of Metallurgical and Materials Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India
[2]Chief Technical Officer, Matverse Vision Pvt. Ltd., Nagpur, Maharashtra, India
[3]Director, Matverse Vision Pvt. Ltd., Nagpur, Maharashtra, India
[4]Professor, Department of Chemistry, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India
[5]Professor (HAG) and HOD, Department of Metallurgical and Materials Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India

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Keywords: PTT, Polypropylene, Polymer blends, Mechanical properties, Processability

Highlights:

- PTT is an important commercial polyester, with excellent fire retardant properties
- However, PTT alone is costly.
- Small quantities of PP has shown to enhance strength significantly.
- Lower MFI value eases processability of the new blend material.
- 5-10 wt.% of PP addition to PTT is advocated.

INTRODUCTION

Beside polymers and polymer composites, the technology of polymer blends has been one of the major areas of research and development with prominent position in polymer science. Polymer blending is useful and versatile strategy for polymer chemist, because of the ability to combine existing polymers into new compositions with commercializable properties. Even with the pandemic times gripping the world, the plastic market grew continuously. In 2020, the global plastic market attained a value of USD 580 billion, which rapidly grew to USD 601 billion in 2022 and is forecasted to grow further at a compound annual growth rate (CAGR) of 4.0% from 2023 to 2030, reaching nearly USD 713 billion [1]. The technology of blending offers the advantage of reduction in research and development expenses compared to the development of new monomers and polymers to yield a similar property profile. Therefore, owing to its obvious properties, polymer blends can be successfully used in industrial, domestic and especially automotive applications.

Poly Trimethylene Terephthalate (PTT) is one of the most important commercial polyester. It is a semi-aromatic, semi-crystalline thermoplastic that can be molded, thermo-formed and spun into fibers as well [2]. PTT shares its characteristics with 2 popular polyesters; Poly Ethylene Terephthalate (PET) and Poly Butylene Terephthalate (PBT). The mechanical and thermo-physical properties of PTT are similar to PET, whereas its molding properties are comparable to PBT. PTT has good tensile and flexural strength, good dimensional stability, excellent flow and surface finish. Like PBT, it also has good chemical resistance to a broad range of chemicals, including gasoline, fat, alcohols, glycols, diluted acids and bases. PTT has found its application mainly in fibers for carpets and specific type of textile (known as Triexta fibers). Fabrics and yarns made from Triexta fiber are strong, very elastic (springs back into shape) and have high abrasion and wrinkle resistance [2]. Because of its good dimensional stability and finishing qualities, PTT is a good choice for engineering applications as well. However, compared to PET and PBT, the PTT polymer is used on a much smaller scale for components like automotive parts, mobile phone housings, and other industrial products.

Thus, looking at the benefits offered by popular polymer blends, like PBT/PET [3,4], Poly Ethylene/Low density Poly Ethylene (PE/LDPE) [5,6], Poly Carbonate/Poly Butylene Terephthalate (PC/PBT) [7,8], Poly Carbonate/Acrylonitrile Butadiene Styrene (PC/ABS) [9,10], Poly Propylene/Poly Styrene (PP/PS) [11,12], Poly Carbonate/Poly Styrene (PC/PS) [13,14], etc., a novel blend between Poly Trimethylene Terephthalate (PTT) and Poly Propylene (PP) is explored in present study.

The PTT polymer is well known for its flame retarding characteristic and it is well established that this property of PTT is not compromised even when it is blended with other polymers [15-19]. However, blending PTT with any other suitable polymer helps to control its crystallinity and other properties like strength and toughness. PTT was first patented by DuPont [20] in 1949. In 2001, Shell Oil Company then patented a synthesis process for PTT with titanium as catalyst.

There are many previous reports that highlight the flame retardant properties of PTT and effect of blending PTT with different polymers on its properties, particularly fire retardancy. H. H. Chuah et al. [21] discloses in patent US2008/0132620A1 a polymeric composition comprising of 75 wt.% PTT, 0.25-5 wt.% flame retardant phosphinate metal salt and 5-25 wt.% other polymers like PET, PBT, PEN, PTN, PA-6 and PA6,6. The flame retardant properties of such compositions reaches up to 280 degrees Celsius. D. G. Madeleine [22] reports in US2011/0159232A1 a novel PTT composition with cyclic phosphonic acid ester exhibiting exceptional flame retardant properties.

There are studies reporting the blending nature of PTT with different polymers as well. S. Padee et al. [23] reports the preparation of biodegradable PLA and PTT blend fibers with a twin screw extruder. K. Kultravut [24] explores the blending of PTT and PLA in the presence of a reactive compatibilizer. X. Mei-Ling et al. [25] explores the miscibility and compatibility of PTT and ABS polymers. K. Wang [26] fabricated the blend of PTT and PTW with varying compositions using the twin screw extruder approach.

Additionally, there are many reports of exploring not only the blends of PTT but the property and structural evaluation of blend-composite systems. R. Sharma et al. [27] explores the effect of nano-organoclay additions on the mechanical properties of PTT/PBT impact modified blends. N. F. Braga et al. [28] reports studies on composites based on PTT/ABS blend with maleic anhydride grafted PTT (PTT-g-MA) as compatibilizer and CNTs as filler. A. Kiziltas et al. [29] reports the fabrication of PET/PTT blend with microcrystalline cellulose (MCC) to prepare composite.

It is a common understanding that the crystallinity of base polymer is largely influenced by the polymer which is used to blend with it. The crystalline properties have a significant effect on the mechanical performance of the blend as well. To achieve a balance between the structure and properties of the blend, it is important to tailor the polymer type and quantity that is used for blending. Hence an attempt has been made in present study to develop a novel PTT/PP blend which is tailored to achieve improved mechanical properties without compromising its structural integrity.

MATERIALS AND METHODS

Materials and Sample Preparation

The PTT (Make: Corterra, Shell Chemical Co., USA) and PP (Make: Reliance Industries Limited) polymers were procured in the form of granules. The blend of PTT and PP were prepared with varying compositions as given in Table 1.

Table 1. Sample details and sample code under study

Sr. No.	PTT wt.%	PP wt.%	Sample Code
1	100	0	P100
2	95	5	P95
3	90	10	P90
4	85	15	P85
5	80	20	P80
6	75	25	P75
7	50	50	P50

The blends were prepared by mechanically mixing the polymer granules in fixed quantities, melt-compounding for blending purpose and then injection molding into the required sample shape. The mixed granules were first pre-heated at 80 degrees Celsius for 4 hours in an air circulating oven prior to melt-compounding. The melt compounding was done using a 25 mm twin-screw extruder (Make: M/s Boolani Engineering Corporation) set to the following temperature zones: Zone I=160 degrees C, Zone II=180 degrees C, Zone III=210 degrees C and Die zone=230 degrees C. The extruded strands were cooled in a water bath and later palletized using the wire cutting unit. These pellets were again dried in oven at 80 degrees C for 4 hours prior to injection molding. The blended granules were used for injection molding as per ASTM standard D3641 using a hydraulic injection molding machine (Make: Electronica, Model: Optima 75-128). An injection pressure of 70 bar was fixed and the temperatures of the four heating zones were maintained at 170, 190, 210, and 230 degrees C. The total cycle time was set as 30 seconds, including 5 seconds of dwell and 15 seconds of cooling.

Testing and Characterization

The injection molded samples were tested for their mechanical performance in terms of tensile and impact strength. The tensile strength was determined in accordance with ASTM standard D638 using a universal testing machine (Make: INSTRON, Model: 4467). An average of five results is reported for Type I dog-bone specimen tested at a crosshead speed of 5 mm/min. The Izod impact strength was measured as per ASTM standard D256 using a pendulum weight of 1.37 kg and a striking velocity of 2.45 m/sec. Five readings are averaged and reported in the present study. Based on the optimum PTT/PP ratio obtained from these tests, further characterization was carried out using X-ray Diffraction (XRD), Differential Scanning Calorimetry (DSC), Melt Flow Index (MFI), Rockwell hardness (L scale), and microscopy.

The XRD patterns were generated using a PAN-alytical X'Pert Pro by scanning the samples over a 2θ range of 10°–100° with a step size of 0.01° and a time per step of 20 s. Each sample was scanned three times, and the data were merged using X'Pert High Score Plus (v3.0.0) to obtain the average XRD diffractogram. The crystallite size was determined directly by the same software using Scherrer's equation.. The hardness of the samples was measured on a Rockwell Hardness Tester (Shri Ram Industries, Model: RA8) on the L scale as per ASTM D785, and the average of ten readings is reported. The DSC, MFI, and microscopy analyses were carried out for pure PTT and only those blends that exhibited improved mechanical properties. DSC was performed in sealed aluminum pans under a nitrogen atmosphere using an average sample weight of 10 mg on a calorimeter (Mettler Toledo, Model: DSC 821). The thermal cycle consisted of heating at 10°C/min up to 260°C, holding for 5 min, cooling at 10°C/min to ambient temperature, and holding again for 5 min. The crystallinity (χc) of the samples was then determined using the following formula:

χ_c= 〖ΔH〗 _m/(〖ΔH〗 _m^o) ×100% (1)

where, 〖ΔH〗 _m is the melt enthalpy of the sample in J/g from DSC and 〖ΔH〗 _m^o is the melt enthalpy of 100% crystalline PTT taken as 146 J/g [30]. MFI of the samples was done by extruding the blend granules in a MFI tester (Make: KAYJAY, Model: 2006/AC) at 240°C temperature using a load of 1.2 kgs and cut time of 30 seconds. An average of three tests for each sample is reported herein. For microstructural investigation, the blends were cryo-fractured and were examined using FESEM (JEOL JSM-7610F) after sputter-coating with a thin platinum layer using a fine coater (JEOL JEC-3000FC) to make them conductive.

RESULTS AND DISCUSSION

Mechanical Properties and Microstructure of PTT/PP Blends

The blends listed in Table 1 were compared with pure PTT in terms of tensile and impact strength, and Figure 1 presents these properties as a function of PP loading. Even small amounts of PP noticeably improved the mechanical strength of PTT blends. Pure PTT showed a tensile strength of 57.39 MPa, which increased to 88.79 MPa with 5 wt.% PP, corresponding to an improvement of about 54%. At 10 wt.% PP, the tensile strength decreased slightly to 83.79 MPa, but still remained about 46% higher than pure PTT; beyond this composition, the tensile strength declined further. A similar trend was observed for impact strength, with the maximum improvement seen for sample P90, where the impact strength increased from 31.3 J/m for pure PTT to 93.8 J/m for the blend containing 10 wt.% PP, representing nearly a threefold increase. This enhancement may be attributed to the soft and crystalline nature of PP, which enables greater energy absorption under impact loading.

However, the deteriorating trend shown by both the tensile strength and impact strength after 10 wt.% PP addition can be credited to the immiscibility between PTT and PP phases after melt-blending [30]. This was confirmed by visible phase separation in the SEM micrographs of the cryo-fractured blend surfaces. Figure 2 shows the SEM micrographs of selected samples P100, P90 and P50.

It can be seen from the SEM micrographs that PP remains immiscible in PTT matrix at all compositions. Even with the change in PP content from 10 wt.% to 50 wt.%, the phase separation is distinctly visible in the blend. The PP phase appears as large and spherical particles dispersed throughout the PTT matrix. This is similar to the findings reported by Lin and Cheng [30]. Thus, it can be said, in small quantities, the separated yet dispersed particles of PP give reinforcing effect, thereby, aiding the blend in sustaining more load during tensile and impact loading. A further increase in PP content will increase the volume of phase separation. In order to verify this, XRD was done for the blends to study the crystallographic changes with PP content.

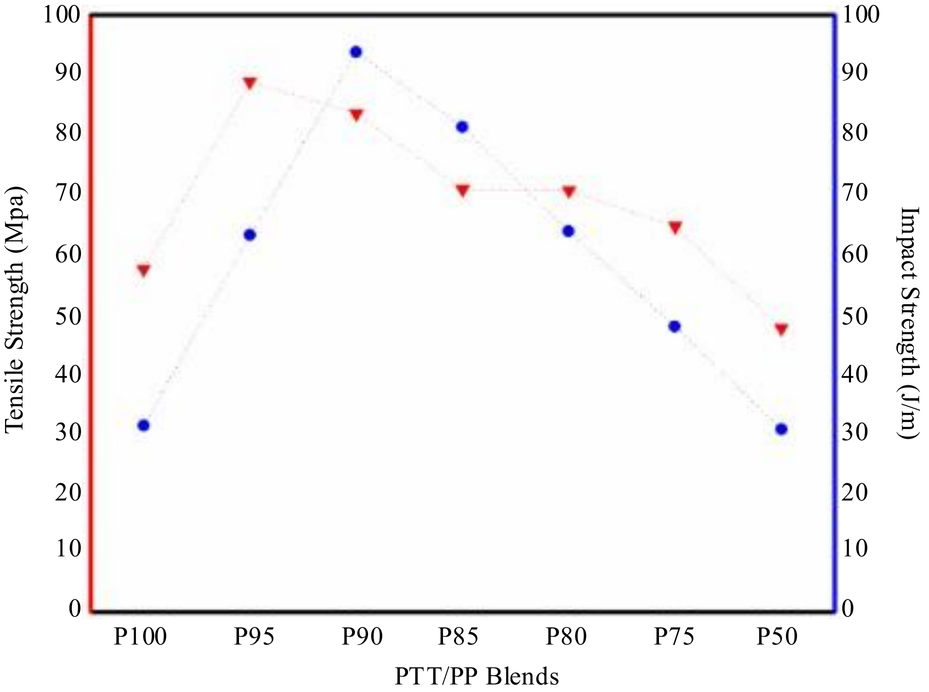

Figure 1. Tensile strength and Impact strength of the PTT/PP blends under study

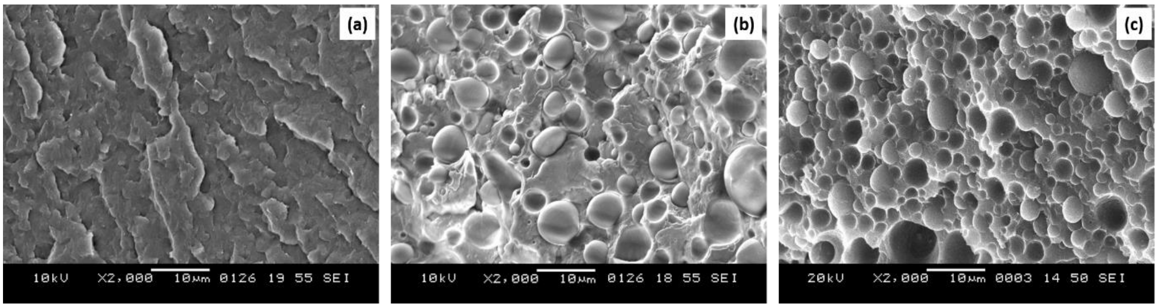

Figure 2. SEM Micrographs for samples (a) P100, (b) P90 and (c) P50

XRD Analysis and Hardness of PTT/PP Blends

Figure 3 shows the XRD diffractograms of all the PTT/PP blend compositions under study as compared with pure PTT and PP. Figure 3(a) also shows the peaks positions in pure PTT and PP polymers. Pure PTT polymer shows characteristics reflections at 14 degrees, 19 degrees and 23 degrees for (010), (012) and (102) crystallographic planes of polymer segments [30,31]. On the other hand, pure PP exhibits characteristic reflections at 13, 16, 17, 20, 21 and 24 degrees for (110), (040), (111), (131) and (041) planes of crystalline phases. It is clear from Figure 3(b) that as the PP content increases, the semi-crystalline nature of the blend changes to crystalline as evident from the sharp peaks. The sample P95 reflects all the peaks of PTT along with the strongest peak of PP at 16 degrees. The intensity of this peak increases with increasing PP content and more PP peaks appear in the blend. The crystalline nature of PP superimposes upon the peaks of PTT with increasing PP content as visible from sample P50. These changes ascertain successful blending of PTT and PP. The crystallite size for the blends under study is tabulated in Table 2.

The crystallite size confirms the claim that the crystalline nature of PP is imparted to the blend as evident by the reducing crystallite size. However, this reduction is analogous to the mechanical properties. For blends P95 and P90, the improvement in the tensile and impact strength can be credited to the smaller crystallite size [32,33]. This behavior is shown by many polymeric systems as well [34-40] and therefore can be confirmed for the PTT/PP blends under study. The blending of PP into PTT, though immiscible, aids in crystallographic rearrangement of the PTT. In small quantities, this effect of PP is beneficial and gives good mechanical strength with improved crystalline structure of the blend. With a further increase in PP content, the phase separation and immiscibility of the phases dominates the positive effect of reduced crystallite size, and thus, deteriorates the mechanical properties.

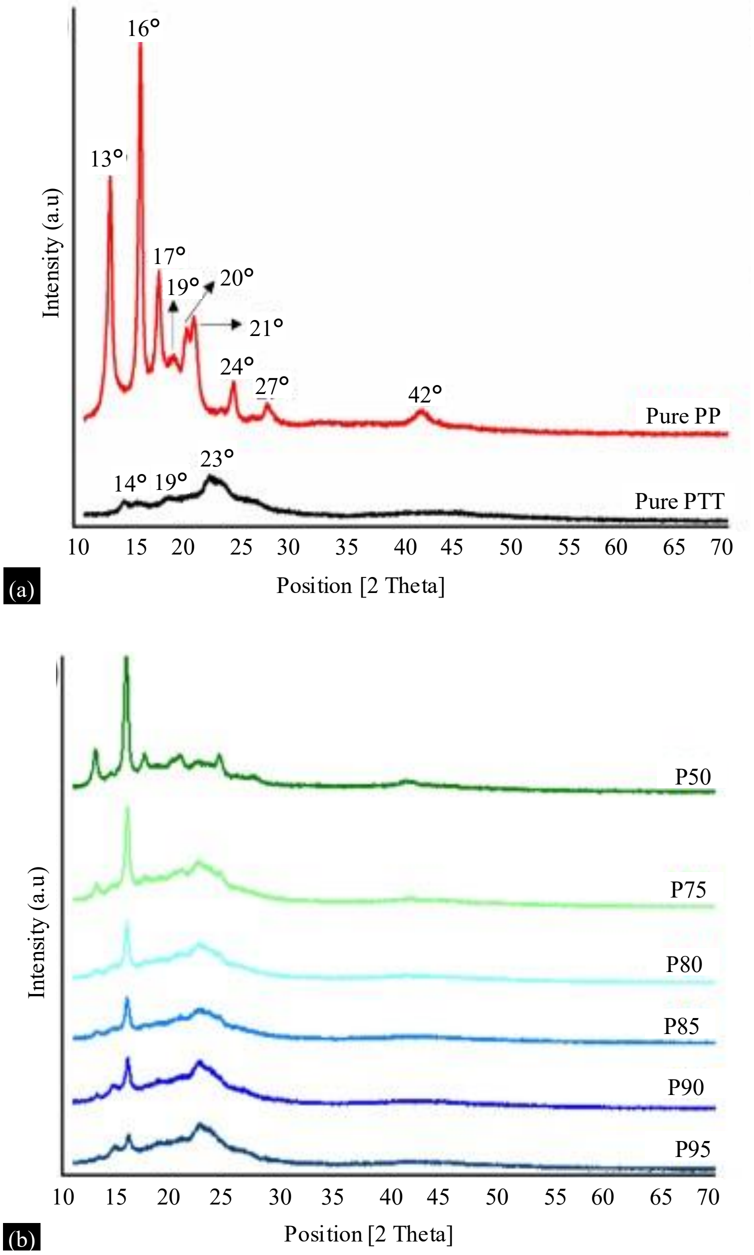

Figure 3. XRD Diffractograms of (a) Pure PTT and PP and (b) PTT/PP blends under study

Table 2 also summarizes the hardness of the blends taken on Rockwell L scale. It is clear from the values that pure PTT is a tough polymer exhibiting maximum hardness amongst the blend compositions under study. It can be seen that the hardness of the blends significantly drops as the PP content increases. As compared to PTT, PP is a crystalline, ductile and soft polymer [17,30]. For blends P95 and P90, at small additions of PP, the marginal reduction in the hardness is not as significant and in fact aids with the load bearing capacity of the blend. A further increase in the PP content increases the extent of phase separation, resulting in an immiscible blend with larger crystallite size and softer nature, ultimately resulting in reduced mechanical properties.

Table 2. Crystallite size and Rockwell hardness (L scale) of PTT/PP blends under study

Samples	Crystallite Size (A)	Rockwell Hardness (L scale)
P100	556	107
P95	249	103
P90	279	99
P85	309	94
P80	320	89
P75	373	84
P50	385	58

MFI and DSC of Selected PTT/PP Blends

The immiscibility of blends can greatly affect the processability of the material on a commercial level. The improvement in the strength without compromising the structural integrity of the polymeric blend system is evident from the above results. Thus, MFI and DSC was done for selected samples and the data is shown in Table 3.

Table 3. MFI and DSC data for selected PTT/PP blends under study

Samples	MFI (gm/10 min)	% Crystallinity (Xc) from DSC
P100	19.81	45.90
P95	16.95	43.64
P90	14.50	40.28

The MFI of the blend is reducing with PP addition. This reduction is ~14% and ~26% for samples P95 and P90, respectively. From processing point of view, a reduction in MFI is very important. The MFI signifies resistance of the polymeric material to flow. A reduction in MFI means the resistance of the new material to flow is less than that of pure PTT. As the resistance to flow reduces, less will be the energy required to fabricate a component from PTT/PP blend under study. Thus, it can be said here that blending PP into PTT is favorable from the processability point of view also. The crystallinity values of the blends further support the claim made through XRD that adding PP to PTT in small quantities (up to 10 wt.%) does not noticeably affect the crystallinity of the blend. Though the % crystallinity value seems to be reducing for P95 and P90 blends, the improvement in the mechanical properties compensates for it. Additionally, this supports the XRD data claiming that the crystallographic structure does change when PTT is blended with PP, however, this does not affect the structural integrity of the blends and thus, these blends can be used for their improved mechanical properties and good processability.

CONCLUSIONS

The present study reports the successful development of PTT/PP polymer blends with enhanced mechanical properties. This improvement does not affect the structural integrity of the material and gives good processability as well. PTT/PP blends with 5-10 wt.% of PP is found to be beneficial for enhancing the mechanical properties of the blends. The improvement in the mechanical properties has been credited to the presence of soft and crystalline nature of PP segments which enhances the load bearing capacity of the blend. Adding PP in small quantities up to 10 wt.% does not noticeably affect the crystallinity of the blend. Additionally, reduced MFI values makes the blends beneficial from processing point of view meaning the resistance of the new material to flow will be less than that of pure PTT. This will make fabrication of the components from the PTT/PP blend easier, energy efficient and economical.

Thus, the addition of 5-10 wt.% of PP into PTT is advocated from present study.

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Declaration of Interest

There are no conflicts to declare.

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