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Research Paper

Development of PP/Recycled-PET Blended Low Speed Wheels to Reduce the Virgin Plastic Usage in the Industry

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Abstract

The increase of plastic usage in different applications has a huge impact on the environment due waste generation. This study was focused not only to find a way to reduce the virgin plastic usage but also to convert a commodity plastic waste into a commercial engineering product. Post consumed polyethylene terephthalate (PET) water bottles were used as a source of recycled PET (r-PET) and blended with commercial grade polypropylene (PP) to produce the center part of low speed wheels. Thermomechanical properties of PP/r-PET blends were investigated along with the effect of compatibilization. The quality of prepared wheels was examined with dynamic drum test and impact test. The addition of recycled PET into polypropylene enhanced the properties of blends and it also supported to maintain the fatigue life of the wheel.

Keywords: Low speed wheels, polypropylene/PET blends, value addition, recycling PET, PP/r-PET blends

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Introduction

Plastics are widely used as packaging materials, construction items, automobile parts, furniture, and toys due to its light weight, durability and versatility [1] [2]. In addition to these key applications, plastics are also used to manufacture apparel, sporting goods, electronics, and stationeries [3]. Almost 99% of total plastic production comes from the chemicals refining from fossil fuels [4]. Polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS) are most widely used commodity plastics in the world. According to the available literatures, world plastic production in 2019 was about 368 million tons [5]. As the plastic production and consumption increase, plastic waste generation also increases. Plastic will take more than 400 years to decompose [6]. Therefore, plastic waste is harming many organisms in various ways because it persists in the environment for a longer time [7]. Hence, reduction of plastic waste is very important. Currently, about 9% of plastic waste is being recycled and 12% is being incinerated [7]. However, the remaining 79% of plastic waste is released to the environment. The degradation of the plastics over the time leaches plastic additives such as stabilizers, harmful colorant moieties, plasticizers, and heavy metals to the environment causing soil and water contamination. The incineration of plastic waste also releases hazardous chemicals into the atmosphere causing air pollution. Eventually, these hazardous chemicals deposit on plants and soil. Being migrating to groundwater or being absorbed by plants, hazardous chemicals from plastic inadvertently enter to human food chain. By looking at these scenarios in the world, our focus was to find a way to minimize the amount of plastic waste, minimize amount of virgin plastics which enter into the world every day, make a sustainable commercial products, and increase the value addition locally.

In this paper, a development of low-speed wheels using blends of virgin polypropylene (PP) and recycled polyethylene terephthalate (r-PET) as a joint investigation of industrial and academia are described. Currently, one of the leading rubber product manufacturing companies in Sri Lanka use considerable amount of virgin polypropylene annually to manufacture low speed wheels. Therefore, minimizing of virgin plastics which enter into the world every day is a great of interest. Furthermore, PET is considered as a 100% recyclable plastic material and it can be re melted and converted into another new product [8] [9]. Since PET is the most recycled material due to its variety of applications such as packaging materials, household items, and garments [10], recycling of these post consumption materials becoming another important area as it can save resources, energy conservation and also it is a positive impact to the environment [11]. When it comes to the plastic blends, there is a huge interest in the blending of PP and PET due to the synergistic thermomechanical properties of PP/PET blends [12]. The incompatibility between PP and PET materials has influenced many researches to lead their investigations to determine suitable compatibilizing agents for PP/PET blends [13-20]. The PP-g-MA (polypropylene-graft-maleic anhydride), PE-g-MA (polypropylene-graft-maleic anhydride), SESA-g-MA (Styrene-Ethylene / Butylene-Styrene-maleic anhydride-graft-maleic anhydride), and SESA-g-GMA (Styrene-Ethylene / Butylene-Styrene-maleic anhydride-graft-glycidyl methacrylate) have been used as compatibilizing agents to develop PP/PET blends not only to obtain homogenous blends but also to improve mechanical properties of blends [13-20]. With compared to other compatibilizing agents, the PP-g-MA compatibilizing agent is widely used in many applications due to the improved mechanical properties of PP/PET blends. Application such as, automobile bumpers using PET/PP/ HDPE blends [21], textile fibers using PP/PET blend [22], and PP/PET blended microfiber for automobile [23] are reported. To the best of our knowledge, here we report the first attempt to develop a low-speed wheel as a high end engineering product by using virgin plastic and the post-consumed plastic waste material (PP/r-PET) with or without a suitable compatibilizing agent.

Materials and Methods

Materials

A commercial grade of polypropylene was used as the main phase of the PP/r-PET blends. The polyethylene terephthalate mineral water bottles were collected from hotels and public waste bins in Colombo, Kalutara, and Monaragala districts in Sri Lanka. A commercial grade of maleic anhydride grafted polypropylene (PP-g-MA) was used as the compatibilizer.

Preparation of recycled PET (r-PET)

The collected post consumed PET bottles were subjected to a cleaning process to remove the impurities, caps, and labels. The bottles were cleaned with tap water and then allowed to air dry. After that the bottles were mechanically crushed using laboratory scale crusher. Mesh size of the crusher machine was set into 1 mm.

Preparation of PP/r-PET pellets

Table 1. PP/r-PET blends formulation

Material	PP/r-PET (90/10) [Kg]	PP/r-PET (80/20) [Kg]	PP/r-PET (70/30) [Kg]	PP/r-PET (80/20) WC[a] [Kg]
PP	90	80	70	80
r-PET	10	20	30	20
Compatibillizer	Yes	Yes	Yes	No

[a]WC denotes "Without Compatibillizer"

Virgin polypropylene, r-PET, and compatibilizer were measured according to the formulations given in Table 1. The size of each trial was selected based on the capacity of the extruder machine. Measured raw materials were mixed manually using a bag before the mixture was fed into the hopper. An industrial extruding machine was used to blend the materials and to pelletize the extruded filaments. Temperature of the extruder was set from hopper to die in eleven heating zones from 210-

310 °C. Extruded filaments were then passed through a water bath for solidification followed by air cooling to remove the moisture. After that extruded filaments were subjected to palletization.

Preparation of Low-Speed Wheel Center, Tensile and Flexural Test Pieces by Injection Molding

The center of the wheel, tensile test pieces, and flexural test pieces were injected in the mold using injection molding machine. Before the production, the blending materials were dried in an industrial scale dryer at 80 °C for 3 h to remove moisture. Temperature of the injection molding machine was set from hopper to nozzle as mentioned in the Table 2.

Table 2. Temperature setting of the injection mold machine

Temperature (°C) (± 05)	Tensile, flexural, test pieces	Center of the low speed wheel
Nozzle	250	270
Zone 1	240	270
Zone 2	220	220
Zone 3	200	220

Characterization

Thermogravimetric Analysis

The thermal stability and decomposition behavior of raw materials and the prepared blends were evaluated by using TA instrument TGA 5500 analyzer in accordance with ASTM E1131. A sample of about 5 mg – 10 mg of all raw materials and blends were tested with the rate of 10 °C/min in a nitrogen atmosphere using high temperature platinum pans. The temperature range was set from 30 to 700 °C except for recycled PET sample because it required higher temperature to appear degradation variations. Therefore, the temperature range for recycled PET sample was set from 30 to 1000 °C to get a more valuable result.

Differential Scanning Calorimetry

Thermal properties of the raw materials and the blends were investigated using SETARAM DSC 131 EVO instrument in accordance with ASTM D3418-15. A sample of about 10 mg – 15 mg of all raw materials and blends were kept on the aluminum crucible. An empty aluminum crucible pan was used as a reference and the analysis was performed under a nitrogen purge in the temperature range of 25–300 °C at a heating rate of 10 °C/min.

Melt Flow Index (MFI)

MFI tests were done to determine the flow properties of the raw materials and the blends. This test was performed in accordance of ASTM D1238. The MFI test temperatures for polypropylene and PP/r-PET blend samples were 230 °C and 250 °C respectively. The weight placed on the piston for both polypropylene and PP/r-PET blend samples were 2.16 kg. The mass of molten polymer was determined in 30 second since both PP and r-PET shows high melt flow rate where it is about 10-25 g/min. Calculation was performed according to the ASTM standard to determine the MFI g/10 min by multiplying the weight of the molten polymer came out within 30 second by 20.

Tensile Test

Testometric M500-50CT Wintest analyzer was used to test the tensile properties of prepared PP/r- PET blends. Test running speed was 5 mm/min and the extension range was set to 600 mm. 5 pieces were tested for each and every trials in accordance of ASTM D638 and the mean values were reported to compare the tensile properties of the blends.

Flexural Test

The Testometric M500-50CT Wintest analyzer was used to test the flexural properties of prepared PP/r-PET blends. Test running speed was 5 mm/min and the span length was adjusted to the value of 16 times the specimen thickness.

For an example: If Specimen thickness is 4.2 mm, span length is 4.2 × 16 = 67.2 mm. 5 pieces were tested for each and every trials in accordance to the ASTM D790 and the mean value was reported here.

Dynamic Drum Test

Dynamic drum test was performed to check the fatigue life of the low-speed wheel by giving some real world conditions. Dynamic drum test is often used to check the fatigue life of the wheels which are used in different industries. Mainly there are two test are carrying out under dynamic drum test, obstacle test for wheels and endurance test for wheels [24]. Both tests are performed to check the ultimate failure time of the wheel by subjecting the sample to real world conditions.

Typically, dynamic drum test is performed by mounting the sample to a ram which can move vertically. This ram helps sample to contact with a large rotating drum. Also the ram will apply a force equal to the maximum capacity of the wheel sample. When the drum starts to rotate, the sample also rotates. Dynamic drum test conditions are listed in Table 3.

Table 3. Dynamic drum test conditions

Parameter	**Value**
Speed	4 km/h
Load	100 kg
Running time with obstacles	15 min
Running time without obstacles	73 min
Total running time	88 min

Impact Test

Table 4. Impact test

Parameter	Value
Pendulum weight	13.73 kg
Drop height	13 inch
Total weight	10 (5 times each side)

Impact test for newly prepared low speed wheels were performed to check the impact resistance of the wheel. This test was performed in accordance of EN 12532: 1996 standard method. The used test conditions and parameters are shown in below Table 4. All the samples were placed in two ways, injection side upward and ejector side upward.

Results and Discussion

Thermogravimetric Analysis

TGA results of raw materials and pp/r-PET blends are shown in the figure 1. The major degradation temperatures of raw materials were in the range from 320 °C to 500 °C. Among the raw materials only r-PET shows two stage decomposition in the range of 320 °C to 500 °C and 500 °C to 700 °C while others, PP and PP-g-MA show one-stage decompositions where it was found within the 320 °C to 480 °C temperature range (Figure 1a). Both r-PET and PP/r-PET show the highest thermal stability than both PP and PP g MA. As compared to both PP and PP-g-MA, the backbone of the PET polymer chain contains benzene rings which are more stable organic motifs so that energy required to break chemical bonds of benzene rings is higher than that of the chemical bonds at the PP and PP-g-MA.

The polarity of PET introduces strong dipole-dipole interactions, while π-π interactions between benzene rings further increase the strength of the intermolecular interactions which ultimately increase the thermal stability of the r-PET and PP/r-PET blends compared to the both PP and

PP-g-MA. The one-stage decompositions of PP and PP-g-MA may be due to the random chain scissions of C–C bonds in the polymer chains with the increment of temperature [25]. Decomposition of PP starts earlier (320 °C) than other two materials. Maleic anhydride grafted polypropylene started to decompose around 350 °C and the decomposition of recycle PET starts at around 385 °C.

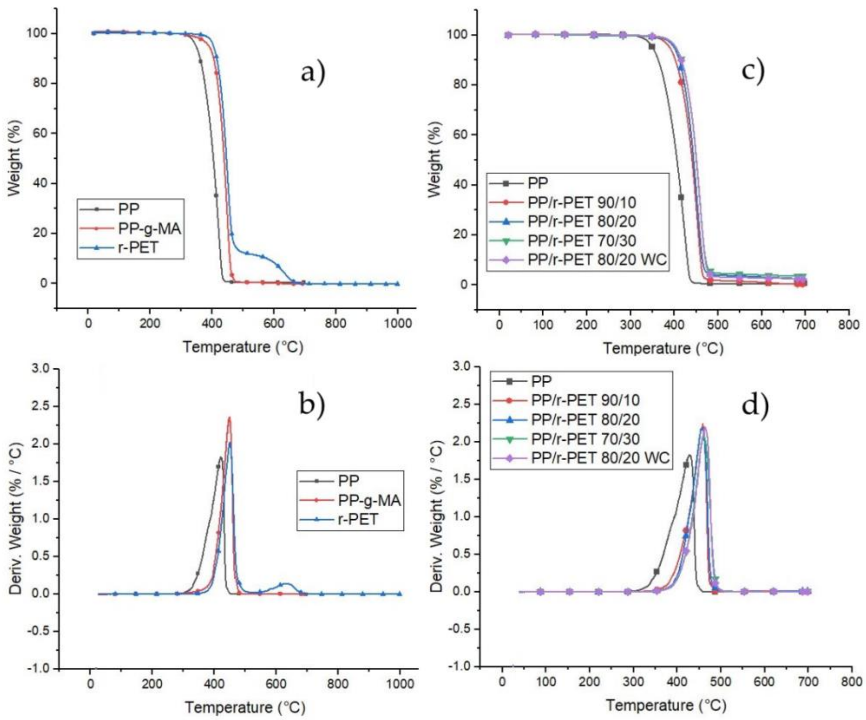

Figure 1. Thermal gravimetric analysis of (a-b) raw materials and (c-d) blends.

The TGA graphs of newly prepared PP/r-PET blends indicate that all the blended samples have higher decomposition temperature than virgin PP (Figure 1b). It means that the addition of recycled PET increases the thermal stability of PP/r-PET blends. All the PP/r-PET blends started to decompose at around 365 °C with compared to the PP decomposition temperature at around 320 °C. The PP/r-PET blend with the ratio of 90/10 started to decompose earlier than other blends duet to the high ratio of PP in the blend. On the other hand, the PP/r-PET blend with the ratio of 70/30 indicated the more thermal stability than other blends and virgin PP due to the high thermal stability of r-PET. The addition of recycled

PET into virgin PP shows increase in the decomposition temperature of all the blends. Most importantly, the one stage decomposition of TGA curves of all the four blends supports the nature of good mixing without any significant phase separation.

Differential Scanning Calorimetry

The DSC analysis was performed to determine the melting temperature and the percentage crystallinity of the PP/r-PET blended samples. Generally, DSC measures the heat flow during endothermic or exothermic process as a function of temperature and time in a controlled environment. The figure 2 indicates the DSC curves of raw materials and PP/r-PET blends. Melting points of the newly prepared blends are closer to the melting point of PP which may be due to the high percentage of PP in the blends also possible homogenous blends of PP and r-PET (Table 5).

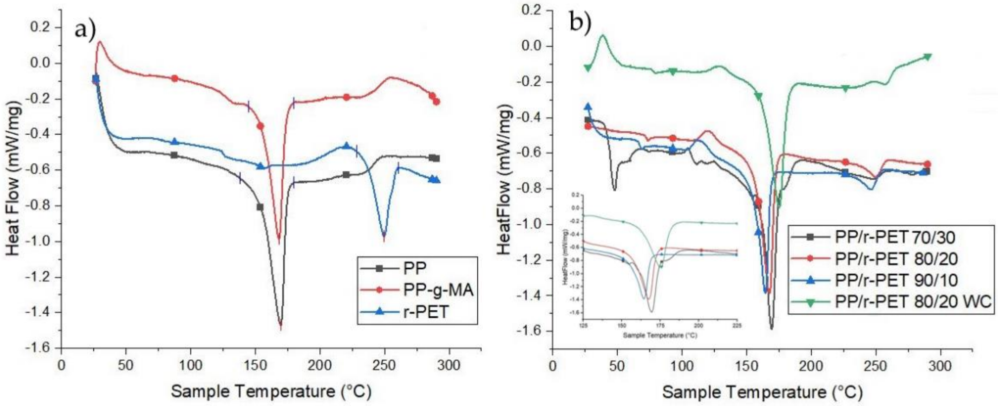

Figure 2. DSC curves of (a) raw materials and (b) PP/r-PET blends.

The percentage crystallinity of the samples was calculated by considering the heat of fusion of samples (Table 5). Heat of fusion of 100% crystalline PP (165.3 Jg^{-1}) were considered to calculate percent crystallinity of the blends as the blends contain more amount of PP than recycle PET using the Equation 1[26].

$$\text{Percent crystallinity} = \frac{\Delta H_f}{\Delta H_{f°}} \times 100\% \qquad \text{Equation 1}$$

Where, ΔH_f is sample's heat of fusion (J/g) and ΔH_f° is heat of fusion (J/g) of 100% crystalline form of the sample.

According to the percent crystallinity results, the crystallinities of blends were slightly increased when increasing the amount of r-PET in PP matrix.

Table 5. Melting point and percentage crystallinity of the samples

Entry	Sample	Melting Range (°C)	Temperature at the peak (°C)	% Crystallinity
1.	PP	129 – 179	169	36
2.	PP-g-MA	141 – 179	168	33
3.	r-PET	224 – 261	249	23
4.	PP/r-PET (90/10)	148 – 178	169	24
5.	PP/r-PET (80/20)	145 – 177	168	30
6.	PP/r-PET (70/30)	145 – 188	170	37
7.	PP/r-PET 80/20 WC[a]	142 – 181	169	30

[a] PP/r-PET (80/20) was prepared without compatibillizer

Melt Flow Index

Table 6. MFI results of PP and PP/r-PET blends

Entry	Sample name	MFI (g/10 min)
1.	PP	8
2.	PP/r-PET (90/10)	8
3.	PP/r-PET (80/20)	11
4.	PP/r-PET (70/30)	12
5.	PP/r-PET 80/20 WC[a]	11

[a] PP/r-PET (80/20) was prepared without compatibillizer

Melt flow index were checked to determine the viscosity of the raw materials (Table 6).

The MFI values were increased when PP was blended with recycled PET from 8 to 12 g/10 min (Table 6, Entries 1-4). These results indicate that the increment of recycle PET content in the blend causes decrease of the viscosity of blends. When virgin PP and r-PET were blended with ratio of 9:1, there was no any increase of the MFI value this could be due to high percentage of PP in the blend.

Tensile Properties

Tensile strength of raw materials and PP/r-PET blends are summarized in the Table 7. The tensile strength of PP/r-PET increases with the increment of the r-PET percentage in the blends since the tensile strength of r-PET is higher than both PP and PP/r-PET blends (Table 7, entry 2 vs entries 3-6). On the other hand, elongation at break decreases when the amount of r-PET increases in the blend since virgin PP (Table 7, entry 1 vs entries 3-6). PP/r- PET (90/10) sample shows the highest elongation at brake value among PP/r-PET blends due to high PP content. The reason for the decrement of elongation at brake when increasing recycled PET is due to the stiffness of PET [18].

Table 7. Tensile properties

Entry	Sample name	Tensile strength (MPa)	Elongation @ brake (%)	Young's modulus (N/mm^2)
1.	PP	24	134	670
2.	PET	42	4	1585
3.	PP/r-PET (90/10)	24	107	929
4.	PP/r-PET (80/20)	25	42	978
5.	PP/r-PET (70/30)	27	26	803
6.	PP/r-PET (80/20) WC[a]	25	84	1130

[a] PP/r-PET (80/20) was prepared without compatibillizer

Tensile strength of raw materials and PP/r-PET blends are summarized in the Table 7. The tensile strength of PP/r-PET increases with the increment of the r-PET percentage in the blends since the tensile strength of r-PET is higher than both PP and PP/r-PET blends (Table 7, entry 2 vs entries 3-6). On the other hand, elongation at break decreases when the amount of r-PET increases in the blend since virgin PP (Table 7, entry 1 vs entries 3-6). PP/r- PET (90/10) sample shows the highest elongation at brake value among PP/r-PET blends due to high PP content. The

reason for the decrement of elongation at brake when increasing recycled PET is due to the stiffness of PET [18].

The Young's moduli of the prepared blends indicate that the addition of r-PET is highly effected to the modulus of the final mixture (Table 7, entry1 vs entries 3-6). These results are not conclusive enough to indicate the effect of r-PET on Young's modulus. However, previously studied have reported that the increment in modulus when increasing the amount of PET added into the PP matrix [18].

Flexural Strength

Table 8. Flexural strength

Entry	Sample name	Flexural strength (MPa)
1.	PP/r-PET (90/10)	69
2.	PP/r-PET (80/20)	71
3.	PP/r-PET (70/30)	73
4.	PP/r-PET (80/20) WC[a]	67

[a] PP/r-PET (80/20) was prepared without compatibillizer

Flexural strengths of the newly prepared PP/r-PET blends were calculated by using the results obtaining from three-point bending test. Sample length, width and the depth were 165 mm, 5.8 mm and 4.2 mm respectively. The flexural strengths of the blends are summarized in Table 8. The flexural strength of the PP/r-PET increases when more r-PET is introduced into the PP matrix (Table 8, entries 1-3). Improved flexural strength indicates that the PP/r-PET blend have good resistance under load (Table 8, entry 1 vs 3). As usually PET has higher flexural strength than PP, it may be the reason for having higher flexural strength in that blend [27].

Effect of Compatibillizer on Thermal and Mechanical Properties of PP/r-PET Blend

The effect of the compatibillizer on thermal and mechanical properties of PP/r-PET blends were investigated by comparing the results of PP/r-PET (80/20) and PP/r-PET (80/20)WC where PP/r-PET (80/20)WC was prepared without any compabillizer.

Both TGA (Figure 1c-d) and DSC (Table 5, entry 5 and 7) results indicate that there are no significant effects on prepared blends by the PP-g-MA compatibillizer. This could be due to the low percentage of r-PET in PP/r-PET blends which level may not cause the phase separation. Similarly, there was no effect of compabillizer on MFI values of PP/r-PET blends since the MFI value recorded for PP/r-PET (80/20) was similar to the that of PP/r-PET (80/20)WC (Table 6, entry 3 and 5).

Although both thermal and rheological properties of PP/r-PET (80/20) blend were not affected due to application of compatibillizer, there were some effects on mechanical properties of PP/r-PET (80/20) blend (Table 7, entries 4 and 6; Table 8, entries 2 and 4). Both elongation at break and Young's modulus were increased when PP-g-MA compatibillizer was used in the preparation of PP/r-PET (80/20) but no change of tensile strength was observed (Table 7, entries 4 and 6). The flexural strength was slightly decreased in the presence of the PP-g-MA compatibillizer indicating more flexibility of PP/r-PET (80/20)WC blend (Table 8, entries 2 and 4).

Testing Quality of Low-speed Wheel

In order to check the quality of the newly prepared low speed wheels, dynamic drum test and impact test were performed.

Dynamic Drum Test

Table 9. Dynamic drum test

Description	Sample name				
	PP/r-PET (90/10)	**PP/r-PET (80/20)**	**PP/r-PET (70/30)**	**PP/r-PET (80/20) WC**	**PP (Control)**
Bonding failure	No	No	No	No	No
Cracks	No	No	No	No	No
Chipping & chunking effect	No	No	No	No	No
Abraded rubber dust	No	No	No	No	No
Rim loosening effect	Slightly	Slightly	Tire separated from rim	Slightly	Slightly
Damage at the center	No	No	Yes	No	No
Temperature at the end of the test (°C)	C [a] - 43 R [b] - 38	C [a] - 42 R [b] - 38	C [a] - 68 R [b] - 52	C [a] - 54 R [b] - 40	C [a] - 57 R [b] - 40

[a] Temperature of center part of the low speed wheel; [b] Temperature of the rubber wheel

The results of dynamic drum test are summarized in Table 9. The parameters of this test were determined based on the company requirements for the particular 125 mm rubber wheel with polypropylene center. According to the results, the fatigue resistances of PP/r-PET low speed wheels are satisfactory when it is compared to the wheel which was prepared using virgin PP (control sample). However, while all the wheels are showing good fatigue life, wheel prepared using PP/r-PET (70/30) has poor fatigue life. The poor fatigue life of PP/r-PET (70/30) may be due to the high percentage of r-PET content in the blend. When the percentage of r-PET in PP/r-PET blends increases elongation at break decreases (Table 7, Entries 3-5) due to the low elongation at break of the PET (Table 7, Entry 2), ultimately the fatigue failure occurs when a minimum strain is reached by the material.

Impact Test

Table 10. Impact test

Sample Name	Injection point upward	Ejector point upward	Statement
PP/r-PET (90/10)	×	×	Damaged at 1st attempt
PP/r-PET (80/20)	×	×	Damaged at 1st attempt
PP/r-PET (70/30)	×	×	Damaged at 1st attempt
PP/r-PET (80/20) WC	×	×	Damaged at 1st attempt
Virgin PP	√	√	Test completed

As the results of shown in the table 10, the wheel prepared using the PP/r-PET blends were not satisfied with the conducted impact test when results were compared to the control sample where it was prepared only using virgin PP. This test was conducted with available resources and international requirements.

Conclusion

This study was carried out to determine the possibility of adding recycled PET into the production of low speed wheel centers and hubs. The addition of r-PET into the virgin PP has shown improved tensile strength, Young's modulus, and flexural strength. However, it also indicated reduction of elongation at brake when more r-PET was included in the blend. The addition of r-PET into the PP matrix shows a fluctuation in melt flow index which indicates viscosity variations in the blend. However, the thermal stabilities of the blends were increased with the increment of r-PET into the PP matrix. In addition, the effect of the compatibillizer was investigated. However, the collected data was not sufficient to declare the effect of compatibillizer on thermomechanical properties of PP/r-PET blends. The quality of the final item was examined by means of dynamic drum test and impact test. The prepared PP/r-PET wheel passed the dynamic drum test according to the customer requirement. However, they did not meet the impact test requirements.

Conflicts of Interest

Authors declare no conflicts exit again this publication.

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