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High-voltage Electrostatic Separation and Equivalent Reuse of Plastics Used in Passenger Vehicle

HONGSHEN ZHANG*, YINGJIE ZHAO, HONGFEI ZHENG
Faculty of Mechanical and Electrical Engineering, Kunming University of Science and Technology, Kunming, 650500, Yunnan province, China

Abstract: *The recycling and high-valued added reuse of automotive plastics have elicited global attention as the number of end-of-life vehicles increase. In the paper, the two-stage high-voltage electrostatic separation is used to explore the sorting of passenger vehicle plastic mixtures of PP, ABS and PVC. The purities of PP, ABS and PVC are all higher than 97%, and the recovery rates are 55%, 93%, and 48%, respectively. Taking PP plastic as an example, the mechanical properties of the recycled materials and the different ratios of recycled and new material mixtures are studied. Results show that the passenger car bumpers reproduced with a 7:3 ratio of new and recycled materials can satisfy the performance requirements. The finding provides a reference for the high additional value reuse of other automotive plastics.*

Keywords: *end-of-life vehicles, passenger vehicle plastics, high-voltage electrostatic separation, bumpers, high-valued added reuse*

1. Introduction

With the development of lightweight technology, plastic is now widely used in the automotive industry because of its high safety, low cost, durability, and smaller weight than other materials [1]. China's passenger car production and sales ranked the first in the world for 11 consecutive years. The discarded passenger vehicles will grow rapidly as well [2]. If not properly treated, these automotive plastics will cause a serious environmental issue and pose a serious threat to people's health and lives. Moreover, because these plastics contain important renewable plastic resources, without recycling will cause a large waste of resources [3,4].

Automotive plastic polymer parts include bumpers, heat dissipation grille, lights, instrument panels (including sub-instrument panels), seats, car headliners, glove boxes, and fuel tanks. The primary plastics used in vehicles include polypropylene (PP), polyurethane (PU), polyethylene (PE), polycarbonate (PC), polyvinylchloride (PVC), polyamide (PA), acrylonitrile–butadiene–styrene (ABS), polyphenylene oxide, polyformaldehyde, polybutylene terephthalate, and polyethylene terephthalate (PET) [5]. During the dismantling process of the end-of-life vehicles (ELVs), the different plastic parts are mixed together commonly. How to separate the different plastics effectively, is the key factor in their recycling process.

High-voltage electrostatic separation is extensively used to recycle plastics and separate powder mixtures because of its good adaptability, high efficiency, and low pollution. In addition, the separation process is not affected by the color of plastics. The paper investigates the separation of passenger car plastic polymers through two-stage high-voltage electrostatic separation, the high-valued added reuse of the separated plastics will be explored as well.

2. Materials and methods

2.1. Electrostatic separation

The tribocharging phenomenon is complicated because it results from the electrical and physical properties of plastic particles, electron transfer, ion transfer, and the operational environment. Triboelectric charging of particles can be applied for electrostatic separation [6].

**email: hongshen@kust.edu.cn.*

The separation process is sensitive to environment, especially to relative humidity [7]. The mixture in a tribocharging device involves multiple particle-to-wall and particle-to-particle collisions, and different particles are charged with opposite charge according to the triboelectric series [8-11]. The amount of transferred charge can be expressed as a function of particle features, such as length ratio, sliding area, front-facing edge, sliding velocity, plane angle, and relative humidity [12,13].

Relevant studies have been conducted to develop electrostatic separation. Iuga analyzed the tribocharging and electrostatic separation of plastics and reported that tribocharging is a statistical process [14]. Based on the collision between particles, Chahinez introduced a simple mathematical model for simulating the outcome of tribo-aero-electrostatic separation process involving mixture of three granular materials [15]. Salama used a fluidized bed to investigate the distribution of electrostatic charge and discovered that a mixture of positively and negatively charged particles exists in all regions of the fluidized bed, confirming the presence of bipolar charging in PE particles [16]. Li demonstrated that a small particle size is better charged than a large one and that high relative humidity impedes the charging effect [12]. Zelmat et al. exhibited that the efficiency of triboelectrostatic separation increases when the inner wall of the cyclone is covered with material located in the triboelectric series between the plastics to be sorted [11]. The air-drag force and the impact of the particles with the electrodes are important to particles movement [17]. Louati found that the separation performance depends on the inter-electrode distance, the signal frequency, the applied voltage and the rotation speed [18].

Through electrostatic separation, Toth et al. recycled plastics from instrument panels of end-of-life vehicles (ELVs) and recovered more than 99% of the plastics from such wastes in the form of a product containing less than 5% impurities [19]. Zhang et al. developed a triboelectrostatic separator to sort PP and ABS plastics from end-of-life passenger vehicles and calculated the rational ranges of the experimental parameters, showing that the sorting rate of PP and ABS plastics exceeds 60% while their purities exceed 95% [20]. Based on a fluidized bed tribocharging system produced between a pair of rotating aluminum disks supplied by two high-voltage DC supplies of opposite polarities, the mixtures of μm-size PVC particles were successfully separated, with high levels of recovery and purity [21]. The separation of a ternary granular plastic mixture was realized with a tribo-aero-electrostatic separator [22].

The research on triboelectrostatic separation is still limited, and the number of end-of-life passenger car plastics increases at a high rate. Automotive plastics perform differently from plastics used in daily life due to their special requirements, such as weather resistance and flame retardancy.

2.2. Materials and apparatus

The PP, ABS and PVC plastics used in the experiment were obtained from Kingfa company, a specialized automotive plastic manufacturer. The size of the plastics was refined to 0.4-0.8 cm. The three materials were mixed, and the ratio of PP, ABS, and PVC in the mixture was 1:1:1, as shown in Figure 1.

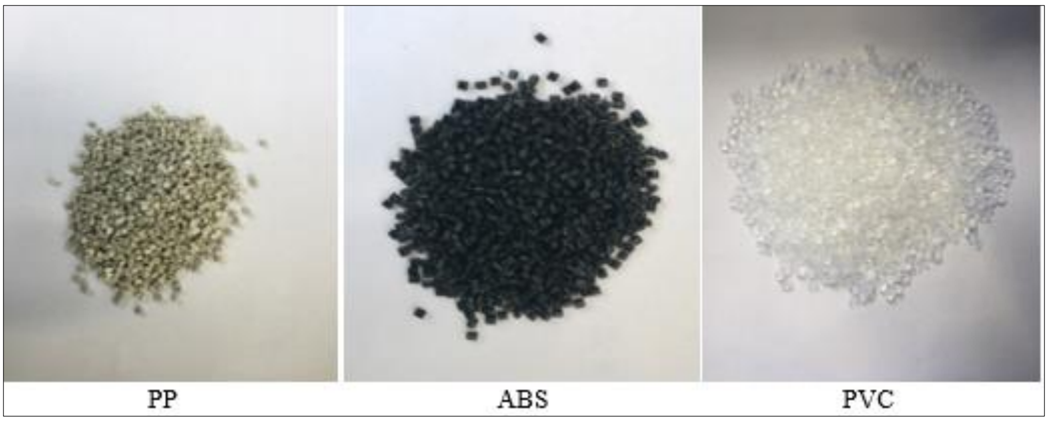


Figure 1. PP, ABS, and PVC samples

The particles physical and chemical properties are shown in Table 1.

Table 1. Comparison of the basic physical and chemical properties of PP, PVC and ABS [23]

Project	General plastics		Engineering plastics
	PP	**PVC**	**ABS**
Density (g/cm^3)	0.90~0.91 (Homogeneous)	1.2~1.4 (Softness)	1.01~1.08
	0.89~0.905 (Gathering)	1.4~1.6 (Hardness)	
Water absorption (% [24h])	< 0.01	0.1	< 0.3
Dielectric constant (ε)	2.2~2.6 (60 Hz)	3.2~3.6 (60 Hz)	2.4~5.0 (60 Hz)
	2.2~2.6 (10^3 Hz)	3.0~3.3 (10^3 Hz)	2.4~4.5 (10^3 Hz)
	2.2~2.6 (10^6 Hz)	2.8~3.1 (10^6 Hz)	2.4~3.8 (10^6 Hz)
Dielectric loss angle Tangent (10^{-4})	< 5 (60 Hz)	< 5 (60 Hz)	30~80 (60 Hz)
	< 5~18 (10^3 Hz)	< 5~18 (10^3 Hz)	40~70 (10^3 Hz)
	< 5~18 (10^6 Hz)	< 5~18 (10^6 Hz)	15~70 (10^6 Hz)
Dielectric strength (V/min) (3.175 mm)	500~660 (Short Time)	425~1300 (Short Time)	350~500 (Short Time)
	450~650 (Phase)	375~750 (Phase)	350~460 (Phase)

In research team, a high-voltage electrostatic separation device [8] was developed to separate the particles.

2.3. Method

Based the separation device, the plastic mixture was separated twice to obtain a pure product. The dry mixture was transported into a rotating friction drum, and the different plastics were charged with different charges. The positive and negative particles were allowed to move to the negative and positive poles in a high-voltage separation chamber, respectively. Thus, the triboelectric series of PP, ABS, PVC, and PMMA (the material of inner wall of the drum) should be determined before sorting. The four plastics triboelectric sequences shown in Table 2.

Table 2. Triboelectric series of plastics

Polarity	Diaz et al. [24]	Shent et al. [25]	Park et al. [26]	Żenkiewicz et al. [9]
Positive (+)	Nylon 6.6	**PU**		
	PVAc	POM		
	PVOH			
	PMMA		**PMMA**	**PMMA**
				PHBV
	PC	PC		PC
				PCL
		PA		PA
			PS	PLA
		ABS	ABS	ABS
			PC	
	PS	PS	PET	
	PE	PE	PE	
	PI			
	PP	**PP**	**PP**	
	PET	PET		
(-) negative	**PVC**	**PVC**	**PVC**	

When the mixture components in this triboelectric series are rubbed against one another, the lower plastic is charged negatively, whereas the upper one is charged positively. The triboelectric series of PP, ABS, PVC, and PMMA is shown below.

(+) PMMA–ABS–PP–PVC (–)

The triboelectric series of PP, ABS, and PVC shows that the products of PVC and the PP/ABS mixture can be obtained in the first stage of separation. Before the second separation, the PP/ABS mixture was prepared for 10 min standing in order to be discharged. Subsequently, the mixture of PP and ABS was fed to the friction drum and rubbed against one another, and then were separated in the chamber. The recovery of PP, ABS, and PVC was achieved. The successful separation depended on the charge-to-mass ratio. Therefore, triboelectrostatic separation requires sufficient charging and a source of electrical potential to generate a strong electric field. The process is as shown in Figure 2.

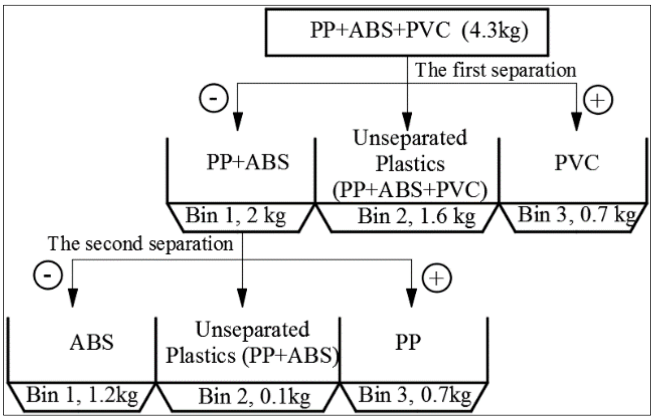


Figure 2. Separation process of PP, ABS, and PVC

2.4. Experiment design

The separation of a three-component plastic mixture is more complicated than that of a two-component one. The different parameters of the electrostatic separator, including temperature (*T*/°), relative humidity (*RH*/%), plastic characteristics, voltage level (*U*/kV), rotational speeds of the friction drum (N_1/rpm) and cylinder electrode (N_2/rpm), distance between two electrodes (*L*/mm), and deflection angle of the rectangular electrode (α/°), should be considered (Figure 3).

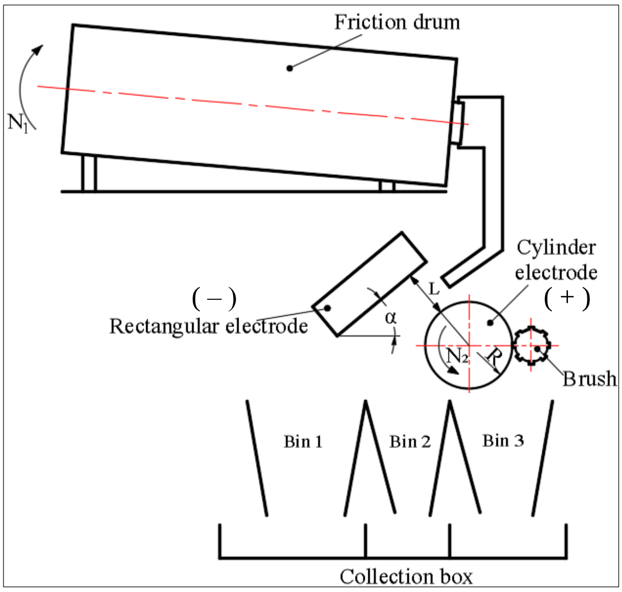


Figure 3. Parameters of the triboelectrostatic separator [20]

To ensure the accuracy of the results, each group of experiments was conducted in same environments. In experimental study, the reasonable values of each parameter were determined based on the single factor analysis method. At the same time, considering the safety of the operator, a voltage below 35kV is selected for the experiment.

This experiment was performed at temperatures between 18°C and 25°C and relative humidity between 40% and 50%. The friction roller speed (N_1) is proportional to the feed rate, which means that the rate at which the plastic falls increases with the increase in N_1. However, due to the limitations of the equipment, one factor was varied in each set of experiments, whereas the other factors were maintained constant. L and α are set to constant values (L = 75 mm and α = 40°) for the single-factor experiments (Table 3).

Table 3. Single-factor experiment settings

Factor	Range	Condition setting
U (kV)	25, 30, 35	N_1 = 30 rpm, N_2 = 25 rpm, L = 75 mm, α = 40°
N_1 (rpm)	25, 30, 35	U = 35 kV, N_2 = 25 rpm, L = 75 mm, α = 40°
N_2 (rpm)	25, 30, 35	U = 35 kV, N_1 = 30 rpm, L = 75 mm, α = 40°

The performance of the recycled plastic product heavily depends on the purity of the recycled plastic, whereas the economic interest of the recycling company depends on the efficiency of the recycling process. The purity of the product can be calculated as.

$$P_{PVC} = \frac{Q_{PVC\text{-}out}}{M_{PVC\text{-}out}} \times 100\% \quad (1)$$

$$P_{PP} = \frac{Q_{PP\text{-}out}}{M_{PP\text{-}out}} \times 100\% \quad (2)$$

$$P_{ABS} = \frac{Q_{ABS\text{-}out}}{M_{ABS\text{-}out}} \times 100\% \quad (3)$$

where the units of P_{PVC}, P_{PP}, and P_{ABS} are in percentages, and the units of other parameters are kg. $Q_{PVC\text{-}out}$, $Q_{PP\text{-}out}$, and $Q_{ABS\text{-}out}$ are the masses of the obtained products PVC, PP, and ABS, respectively, all obtained from the collection box. $M_{PVC\text{-}out}$ is the mass of produced PVC; $M_{PP\text{-}out}$ is the mass of produced PP; $M_{ABS\text{-}out}$ is the mass of produced ABS. $M_{PVC\text{-}out}$, $M_{PP\text{-}out}$, and $M_{ABS\text{-}out}$ include impurities; for example, $M_{PVC\text{-}out}$ actually comprises PVC and impurities of PP and ABS.

The recovery rate can be calculated based on the purities of PP, ABS, and PVC with the following formulas.

$$R_{PVC} = \frac{M_{PVC\text{-}out} \times P_{PVC}}{M_{PVC\text{-}in}} \times 100\% \quad (4)$$

$$R_{PP} = \frac{M_{PP\text{-}out} \times P_{PP}}{M_{PP\text{-}in}} \times 100\% \quad (5)$$

$$R_{ABS} = \frac{M_{ABS\text{-}out} \times P_{ABS}}{M_{ABS\text{-}in}} \times 100\% \quad (6)$$

where the units of R_{PVC}, R_{PP}, and R_{ABS} are in percentages, and the units of $M_{PVC\text{-}in}$, $M_{PP\text{-}in}$, and $M_{ABS\text{-}in}$ are kg. $M_{PVC\text{-}in}$ is the mass of PVC fed to the separator; $M_{PP\text{-}in}$ is the mass of PP fed to the separator; and $M_{ABS\text{-}in}$ is the masses of ABS fed to the separator.

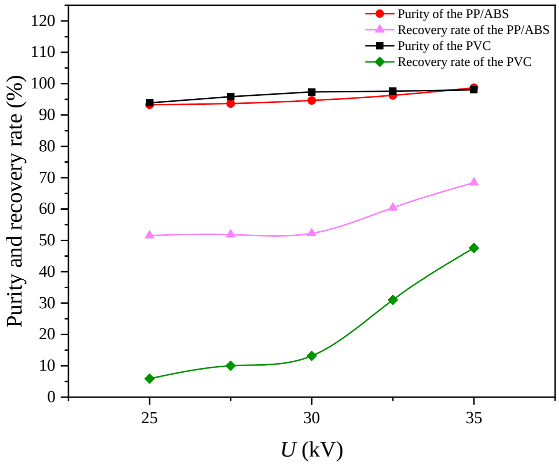
3. Results and discussions

3.1. First stage of separation

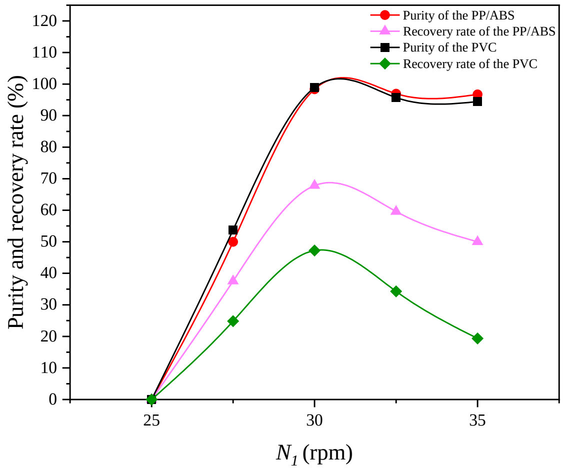
The results of the single-factor experiment for the first stage of separation of PP, ABS, and PVC plastics are shown in Figure 4. The individual constituent elements of the PVC and PP/ABS blends can be obtained in the first stage of sorting. The purity is 98%, whereas the recovery rate of the PVC and PP/ABS blends are 48% and 68%, respectively. The results can be obtained from the experimental charts, and the most suitable values for the first sorting of PP, ABS, and PVC can be determined.

- Effects of high voltage levels (*U*)

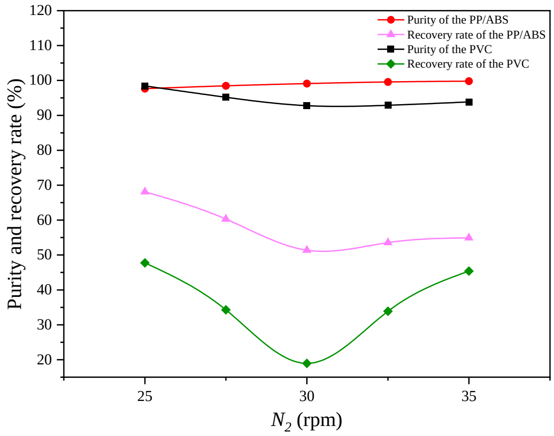
As shown in Figure 4a, the change of *U* has no obviously affected on the purity of PVC and PP/ABS blends. By contrast, the recovery rate of the blends increases with the increase in *U*. During the experiments, discharge occurs when *U* exceeds 40 kV; such a phenomenon can cause injury to the operator. On the basis of purity and recovery rate, 35 kV is a reasonable value for *U* at the first stage of sorting.



(a) Recovery rates and purities of PVC and PP/ABS at different *U*



(b) Recovery rates and purities of PVC and PP/ABS at different N_1



(c) Recovery rates and purities of PVC and PP/ABS at different N_2

Figure 4. Single-factor experiments for the first separation

- Effect of N_1

The highest purity and recovery rate of the PVC and PP/ABS blends are obtained when the friction drum speed is 30 rpm (Figure 4b). The reason is that the feeder changes from continuous feeding to intermittent feeding at low friction drum speed. Moreover, an excessive amount of plastic is dropped into the sorting chamber, which prevents the efficient separation at high friction drum speed. When N_1 is below 25 rpm, most of the PVC and PP/ABS blends are dropped into the wrong collection box because a large amount of plastic remains in the outlet. This phenomenon neutralizes the charge in the plastic and prevents the plastic from being affected by the electric field forces. When the N_1 = 25 rpm, the purity and recovery rate of the PVC and PP/ABS blends are considered zero. Therefore, the results suggest that a reasonable value for N_1 at the first stage of sorting is 30 rpm.

- Effect of N_2

As shown in Figure 4c, the purity of the PP/ABS mixture increases with the increase in the N_2 of the cylindrical electrode. However, when N_2 is 30 rpm, the purity and recovery rate of the plastic obviously decreases, and the plastic adhering to the cylindrical electrode falls into the wrong collection box due to centrifugal force and occupies the area of the electrode. If the rotation speed of the electrode is very slow, the plastic that enters first will be adsorbed on the surface of the electrode, but as time goes by, the surface of the electrode will be full of plastic, so the subsequent plastic will not be adsorbed on the surface of the electrode, resulting in a low PVC recovery rate. The findings therefore indicate that a reasonable value for N_2 at the first stage of separation is 25 rpm.

3.2. Separation of the second stage

The PP/ABS mixture obtained from the first stage of separation was used in the second stage. The results are shown in Figure 5. After the second stage of separation, PP and ABS elements are obtained with productivities of 55% and 93% and purities of 99% and 97%, respectively. The most suitable values for this separation stage can be determined from the graphs.

- Effects of U

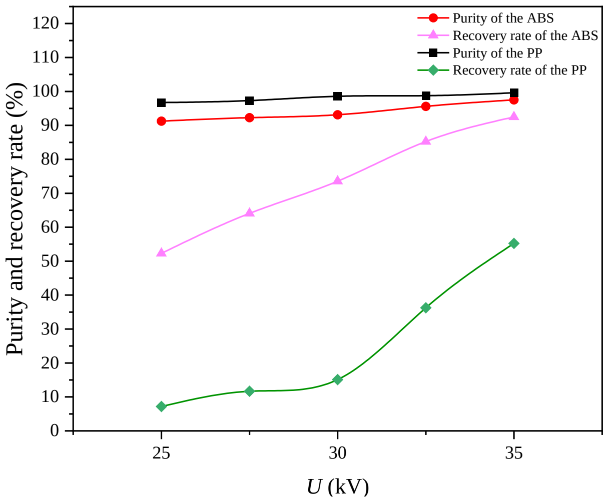
During the experiment, high voltage levels generate a strong electric field (Figure 5a). The plastic is easily attracted to the electrode, and thus causes the purity and recovery rate of PP and ABS to increase with increasing voltage. PP and ABS acquire sufficient charge after friction and therefore easily separate, at low voltage levels. The voltage change has no effect on the purity of the plastic. On the basis of the results, a reasonable value for U at the second stage of separation is 35 kV.

- Effect of N_1

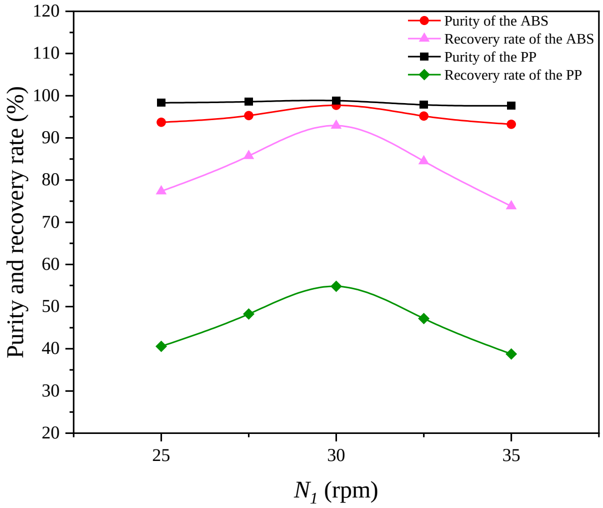
As shown in Figure 5b, the change in drum rotation speed has no effect on the purity of PP and ABS because these plastics have sufficient charges, and the plastic moves to the electrode with opposite polarity regardless of the change in N_1. However, the change in N_1 exerts a significant effect on the recovery rate of the elements due to the change in the feed method. The best separation is achieved when N_1 is 30 rpm.

- Effect of N_2

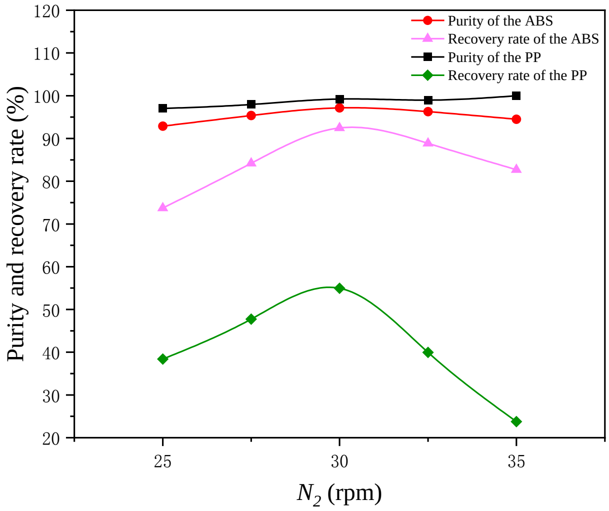
As shown in Figure 5c, the highest purity and recovery rate are achieved when the rotational speed of the cylindrical electrode is 30 rpm. The recovery rate of ABS increases to 93%. During the experiment, the recovery rate of PP obviously increases with the increase in N_2 because the PP attached to the surface of the cylindrical electrode can be timely removed to obtain additional area for the plastic. However, when N_2 is extremely fast, the PP adhering to the electrode leaves the electrode surface. The experimental results indicate that, a reasonable value for N_2 at the second stage of separation is 30 rpm.



a) Recovery rates and purities of PP and ABS at different *U*



b) Recovery rates and purities of PP and ABS at different N_1



c) Recovery rates and purities of PP and ABS at different N_2

Figure 5. Single-factor experiments of the second separation

3.3. Equivalent reuse of passenger cars PP

With the popularity of design for recycling, PP becomes an important material for automotive bumpers due to its balanced mechanical properties, good heat resistance, and without pungent smell. In the study, the performance of the recycled PP polymers is evaluated, and the feasibility of reusing recycled PP into new automotive bumper is explored, which can provide a reference for the high value-adding recycling of automotive plastics.

The process for bumper plastic equivalent reusing involves the performance testing of recycled materials, blends, and injection molding of parts.

3.4. Preparation of recycled passenger cars PP plastic

The recycled PP passenger vehicle bumpers were produced for Volkswagen China in March 2006, by the relevant parts manufacturer. After pretreatment, coating removal, separation, and pelletizing, passenger car PP plastic is recycled (Figure 6).

Figure 6. Recycled PP plastic

The performances of the regenerated bumper particles were tested according to the ISO 1172:1996, ISO 527, and ISO 178 and 179 test methods, results were shown in Table 4.

Table 4. Performances of the recycled bumper particles at normal temperature (23°C)

No.	Test items	Unit	Test results	Required value of new material
1	Tensile yield strength	MPa	16.9	≥15
2	Tensile rupture strength	MPa	13.2	≥15
3	Elongation at break	%	62.1	≥20
4	Bending strength	MPa	20.1	≥15
5	Flexural modulus of elasticity	MPa	686	≥650
6	Notch impact strength	kJ/m^2	31	≥15

As indicated by the results of the mechanical properties tests, the recycled PP materials are maintained in good condition. The results demonstrate good prospects for equivalent performance applications.

3.5. Performances testing of mixed PP

In order to preliminary explore the performances of recycled and new PP mixtures, the new and recycled PP materials mixed at a certain ratio of 9:1, 8:2, 7:3 and 6:4, and their performances were tested, shown in Table 5.

Table 5. Mixed bumper materials performance test

No.	Mixing ratio of the new and recycled material	Tensile yield strength (MPa)	Tensile rupture strength (MPa)	Elongation (%)	Bending strength (MPa)	Bending modulus of elasticity (MPa)	Notch impact strength (kJ/m^2)
1	All new materials	17.5	17.5	469	26.7	1040	40.3
2	9:1	17.2	17.2	467	25.9	1018	32.8
3	8:2	17.2	17.2	472	26.2	960	32.5
4	7:3	16.9	16.9	457	25.3	916	30.9
5	6:4	17.3	17.3	446	24.9	923	29.2

As shown in Table 5, when the ratios of new and recycled material are 7:3 and 6:4, both of them meet the production requirements of bumper materials. However, the tensile yield strength, fracture strength and bending modulus of elasticity of 7:3 mixtures are lower than that of 6:4. Hence, to be on the safe side, the ratio of 7:3 was selected as the proportion of materials for bumper reproduction.

3.6. Performance testing of injection molded bumper

With the assistance of Yanfeng Visteon, bumpers with recycled and new materials, were manufactured (Figure 7).

(a) front section

(b) back section

Figure 7. Bumper produced by mixed materials

In terms of appearance, no difference was observed between brand-new material bumpers and bumpers manufactured with new and recycled PP. Therefore, the general mechanical properties, such as tensile strength, bending strength, flexural modulus and notched impact strength, should be compared. In order to meet the operation needs of the passenger vehicle, several tests, including Vicat heat deflection temperature test; constant climate test with high, low and condensing water; chemical resistance test; aging resistance test; sunlight simulation test, paint mesh cutting test; and water rinse test, should be conducted.

3.7. Mechanical properties of manufactured bumper

Test samples were taken from the finished parts of the bumper before the test. The parameters of the test environment are as follows: pretreatment temperature = 23 ± 2°C and humidity = 50% ± 10% RH. The test results are presented in Table 6. To observe the differences in the performance of the new material and recycled plastic bumpers, the corresponding values of the new material are also listed in the table.

Table 6. Performance test of the bumper mixed materials

No.	Test project	Material		Testing basis and conditions	Standard value	Test result
1	Density (g/cm^3)	New material		TL52631:2005 ISO 1183-1:2004	0.97±0.02	**0.975**
		Mixes				**0.965**
2	Talcum powder content (%)	New material		TL52631:2005 ISO 3451-1:1997	10±2	**11.8**
		Mixes				**10.8**
3	Tensile stress (MPa)	New material		TL52631:2005 ISO 527-2:2012	≥15	**19.2**
		Mixes				**18.6**
4	Fracture elongation (%)	New material		TL52631:2005 ISO 527-2:2012	≥20	**57.7**
		Mixes				**57.2**
5		Room temperature	New material	TL 52631:2005 ISO 178:2010-A	≥15	**24.7**

	Bending strength (MPa)	23°C	Mixes		≥15	**23.0**
		High temperature 80°C	New material	Same as above	≥5	**7.40**
			Mixes			**8.10**
		Low temperature -30°C	New material	Same as above	≤85	**58.2**
			Mixes			**56.1**
6	Bending modulus (MPa)	Room temperature 23°C	New material	Same as above	≥650	**1200.3**
			Mixes			**1052.8**
		High temperature 80°C	New material	Same as above	≥110	**356.9**
			Mixes			**383.3**
		Low temperature -30°C	New material	Same as above	≤3500	**3297.6**
			Mixes			**2966.8**
7	Notch impact strength (kJ/m^2)	New material		TL52631:2005 ISO 179-1/1eA:	No fracture or partial fracture	**39.1 P**
		Mixes				**27.6 P**
8	Vicat heat deformation (°C)	New material		ISO 306:2005 Method A	≥115	**120.8**
		Mixes				**120.8**

The data in the table indicated that the performance of the plastic bumper, manufactured with new and recycled materials, are close to the new ones. The results showed that the former satisfies the requirements for passenger car bumper parts. The production of new-recycled materials at a certain ratio not only reduces the production cost, but also the discarded materials can be reused, saving raw materials. The findings provide a reference for the high additional value reuse of other passenger car plastics.

In summary, the application of recycled passenger car plastic reused in vehicle exploration was realized in the research. This application maximizes the utilization value of automotive plastic parts, improves the utilization rate of the resources, reduces the pollution emissions during the recycling process, and meets green design principle.

4.Conclusions

Two-stage high-voltage electrostatic separation for the ternary end-of-life passenger vehicles plastics, PP, ABS, and PVC, was performed. Furthermore, the high value-added reusing of recycled PP was explored, which provided a reference for realizing the high value-added recycling of end-of-life passenger vehicles plastics. The results provided the following conclusions.

In the first stage separation of PP, ABS, and PVC, the purity of the PVC and PP/ABS blends were higher than 98%, and the production rates were 48% and 68%, respectively. In the second stage, the PP/ABS mixture was separated with a purity of more than 97% and production rates of 55% and 93%. The suitable values of U, N_1, and N_2 for two stages were 35 kV, 30 rpm, and 25 rpm.

On the basis of the performance study of mixing new and recycled materials in different ratios, the bumper reproduce ratio of the new and recycled materials was 7:3. The ratio satisfied the production requirements of new automobile bumpers.

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