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A novel process for separation of polycarbonate, polyvinyl chloride and polymethyl methacrylate waste plastics by froth flotation

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ABSTRACT

A novel process was proposed for separation of ternary waste plastics by froth flotation. Pretreatment of plastics with potassium permanganate ($KMnO_4$) solution was conducted to aid flotation separation of polycarbonate (PC), polyvinyl chloride (PVC) and polymethyl methacrylate (PMMA) plastics. The effect of pretreatment parameters including $KMnO_4$ concentration, treatment time, temperature and stirring rate on flotation recovery were investigated by single factor experiments. Surface treatment with $KMnO_4$ changes selectively the flotation behavior of PC, PVC and PMMA, enabling separation of the plastics by froth flotation. Mechanism of surface treatment was studied by Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and X-ray photoelectron spectrum (XPS). Effect of frother concentration and flotation time on flotation behavior of plastic mixtures was further studied for flotation separation. The optimized conditions for separation of PC are $KMnO_4$ concentration 2 mmol L^{-1}, treatment time 10 min, temperature 60 °C, stirring rate 300 rpm, flotation time 1 min and frother concentration 17.5 mg L^{-1}. Under optimum conditions, PVC and PMMA mixtures are also separated efficiently by froth flotation associated with $KMnO_4$ treatment. The purity of PC, PVC and PMMA is up to 100%, 98.41% and 98.68%, while the recovery reaches 96.82%, 98.71% and 98.38%, respectively. Economic analysis manifests remarkable profits of the developed process. Reusing $KMnO_4$ solution is feasible, enabling the process greener.

1. Introduction

Plastics have been widely applied in our daily life and various industries, due to their versatile properties. An enormous amount of waste plastics are generated because of mass consumption and short life span of plastics. Traditionally, plastic wastes are mainly disposed by landfill and incineration (Simoneit et al., 2005; Zhou et al., 2014), resulting in serious environmental pollution and significant damage to human health (Sigler, 2014; Thompson et al., 2009). Recycling, as an environment-friendly way, receives increasing attention, owing to the benefits of reducing the negative effects on environment and displacing partially virgin plastics produced from refined fossil fuels (Siddique et al., 2008).

Generally, plastic recycling encompasses four activities: collection, separation, processing and marketing (Shent et al., 1999). Due to the difference in chemical and thermal properties, mixed plastic waste (MPW) cannot be processed or recycled directly. For example, a tiny part of polyvinyl chloride deteriorates the nature of other plastics (Sadat-Shojai and Bakhshandeh, 2011). Plastic separation is imperative for recycling of MPW, and it is the bottleneck of recycling process. In the past decades, great efforts have been devoted to provide effective, inexpensive and reliable methods for separation of MPW, such as froth flotation (Wang et al., 2013; Güney et al., 2015; Yenial et al., 2013), density separation (Richard et al., 2011; Pongstabodee et al., 2008), electrostatic separation (Wei and Realff, 2005; Li et al., 2015), and hyperspectral imaging method (Serranti et al., 2011). The similar properties of plastics, such as density, dielectric constant and surface hydrophobicity (Shent et al., 1999), obstruct significantly application of the proposed techniques. Separation based on the difference in density is ineffective for MPW with overlapping density. Tribo-electrostatic separation is difficult to control the polarity of charged plastics (Li et al., 2015).

Froth flotation, as an alternative method, is proved to be effective for separation of MPWs at bench scale (Wang et al., 2015; Singh, 1998). The basis of froth flotation is selective attachment of bubbles on plastic particles to be separated. The natural hydrophobicity of most plastics is the particular challenging for froth flotation. The surface hydrophobicity necessitates selective wetting of plastic components. Flotation separation of plastics

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was achieved with the help of appropriate wetting agents (Saisinchai, 2013; Abbasi et al., 2010; Wang et al., 2014). Recently, surface treatment was also developed for flotation separation, such as flame treatment (Pascoe and O'Connell, 2003), ozonation (Okuda et al., 2007), thermal treatment (Guney et al., 2013), boiling treatment (Wang et al., 2014), alkaline treatment (Wang et al., 2015) and ammonia treatment (Wang et al., 2014), microwave treatment (Thanh Truc and Lee, 2016), and nano-metallic particles (Mallampati et al., 2016). Surface treatment is more reliable and requires less chemical reagents, which reduces the problem of waste water (Wang et al., 2014). In our previous study (Wang et al., 2015), surface treatment with potassium permanganate changed selectively the flotation behavior of plastics through oxidization action, enabling separation of plastics by froth flotation. Potassium permanganate treatment is different from alkaline treatment, the former leads to oxidization of plastics while the latter results in destruction of ester bond in plastic structure.

Polycarbonate (PC), polyvinyl chloride (PVC) and polymethyl methacrylate (PMMA) are commonly found together in plastic products, such as electric appliances, household and automotive products. Moreover, various products mainly consisted of these plastic can be mixed in waste streams when they are discarded. As recycling of plastics is limited by difficulties in the separation step, the development of a separation technique that can recycle plastics is a growing necessity. In this work, a novel process was proposed for separation ternary plastics including PC, PVC and PMMA by froth flotation combined with surface treatment.

2. Materials and methods

2.1. Materials

Samples of three different kinds of waste plastics, including PC, PVC and PMMA, were obtained from commercial sources. The sieve size fractions of plastic samples used in this study were 2.0–3.2 mm. The average density of PC, PVC and PMMA samples was 1.19 g cm^{-3}, 1.38 g cm^{-3} and 1.18 g cm^{-3}, respectively. Before experiments, plastic particles were washed with tap water and dried at room temperature. Plastic samples were of different colors, which made analysis of purity of the plastics through manual sorting at the end of each experiment easier. Potassium permanganate ($KMnO_4$) was used for surface treatment, and methyl isobutyl carbinol (MIBC) was used as frother. Tap water was used throughout flotation tests.

2.2. Potassium permanganate treatment

Plastic samples were treated with $KMnO_4$ solution in 500 mL beaker. The mass fraction of plastic particles was 7.5% (15 g plastics in 200 mL $KMnO_4$ solution) for single plastic, and that for plastic mixtures was approximate 10% (21 g plastics in 200 mL $KMnO_4$ solution) with mass ratio of 1:1:1. An electric mixer with thermostat-controlled water bath (JJ-4A-B, Chang Zhou Ao Hua Instruments Co., LTD, China) was employed for $KMnO_4$ treatment. After surface treatment, the particles were taken out from $KMnO_4$ solution by filtering, rinsed with tap water, and soaked in tap water for 5 min before flotation experiments. Contact angles of PVC before and after surface treatment were determined as previously reported (Wang et al., 2014). Fourier transform infrared spectroscopy (FTIR) were carried out using a Nicolet Avatar 360 FTIR spectrometer (Nicolet Magua Corporation, USA) in the wave regions between 4000 and 400 cm^{-1}. Surface morphology of PC and PVC before and after surface treatment was determined by Quanta FEG 250 scanning electron microscopy (SEM) equipped with energy dispersive spectrometer (EDS). Surface elements of plastic samples were analyzed with an X-ray photoelectron spectroscope (XPS) (ESCALAB 250Xi, Thermo Fisher Scientific).

2.3. Flotation experiments

Flotation tests were conducted using a self-designed flotation column with a height of 170 mm and a diameter of 30 mm. Air was passed through the sand core to produce gas bubbles, and an adjustable air-pump (Guangdong Hailea Group Co., Ltd) with maximum airflow rate of 7.2 ml min^{-1} was employed. The mass fraction of plastic used for floatation tests was about 2%. MIBC was added into the flotation column before flotation experiments. At the end of flotation tests, the floated and non-floated plastic particles were collected, rinsed, dried and weighed.

The schematic diagram of experimental setup is shown in Fig. S1. First, effects of $KMnO_4$ treatment on flotation behavior were studied separately for PC, PVC and PMMA, with respect to $KMnO_4$ concentration, treatment time, temperatures and stirring rate. Flotation tests were carried out after surface treatment of simple plastic under experimental conditions. Then, the influence of frother concentration and flotation time on flotation behavior of PC, PVC and PMMA mixtures was studied after surface treatment of plastic mixtures. Under the optimum conditions, separation of PC from PVC and PMMA plastics was achieved by flotation combined with $KMnO_4$ treatment. Separation of PVC and PMMA was further conducted after considering the effects of treatment time, temperatures, frother concentration and flotation time. The separated products were manually sorted according to the difference in color. The flotation recovery and purity of each plastic in the floated and non-floated products were calculated based on mass balance (Eqs. (1) and (2)). The results were obtained from at least three experiments.

$$\phi_{iF} = \frac{m_{iF}}{m_{iF} + m_{iS}} \tag{1}$$

$$\eta_{iF} = \frac{m_{iF}}{m_{iF} + m_{jF}} \tag{2}$$

where φ_{iF} and η_{jF} are the recovery and purity of component i in float product, respectively, %; m_{iF} and m_{iS} are the mass of component i in float and sink product, respectively, g; m_{jF} is the mass of component j in float product, g.

3. Results and discussion

3.1. Separation of PC from PVC and PMMA

3.1.1. Surface treatment of PC, PVC and PMMA

Fig. 1 shows the flotation recovery of PC, PVC and PMMA as a function of $KMnO_4$ concentration, treatment time, temperature and stirring rate. As shown in Fig. 1, PC, PVC and PMMA possess superior natural floatability, since the flotation recovery of untreated samples is 100%. Treatment with $KMnO_4$ solution has significant effects on the flotation recovery of PC, PVC and PMMA. In Fig. 1(a), the flotation recovery of three samples reduces sharply with increasing of $KMnO_4$ concentration, especially for PC. At $KMnO_4$ concentration of 2 mmol L^{-1}, the flotation recovery of PC is reduced to 0.54%. This can be due to oxidation action of $KMnO_4$ (Wang et al., 2015), which can be enhanced by higher concentration.

Fig. 1(b) demonstrates that the flotation recovery decreases with increasing of treatment time. When treatment time is 10 min, the flotation recovery of PC is reduced remarkably to 0.42%. The flotation behavior of PVC and PMMA is similar under the fixed conditions. Sufficient contact of plastic particles with $KMnO_4$ reduces the flotation recovery. As to separation of PC from