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Research article

Sustainable development of tyre char-based activated carbons with different textural properties for value-added applications

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ABSTRACT

This paper aims at the sustainable development of activated carbons for value-added applications from the waste tyre pyrolysis product, tyre char, in order to make pyrolysis economically favorable. Two activation process parameters, activation temperature (900, 925, 950 and 975 °C) and residence time (2, 4 and 6 h) with steam as the activating agent have been investigated. The textural properties of the produced tyre char activated carbons have been characterized by nitrogen adsorption–desorption experiments at −196 °C. The activation process has resulted in the production of mesoporous activated carbons confirmed by the existence of hysteresis loops in the N_2 adsorption–desorption curves and the pore size distribution curves obtained from BJH method. The BET surface area, total pore volume and mesopore volume of the activated carbons from tyre char have been improved to 732 m^2/g, 0.91 cm^3/g and 0.89 cm^3/g, respectively. It has been observed that the BET surface area, mesopore volume and total pore volume increased linearly with burnoff during activation in the range of experimental parameters studied. Thus, yield-normalized surface area, defined as the surface area of the activated carbon per gram of the precursor, has been introduced to optimize the activation conditions. Accordingly, the optimized activation conditions have been demonstrated as an activation temperature of 975 °C and an activation time of 4 h.

1. Introduction

The global amount of scrap tyres generated increases on an annual basis. This creates a serious waste management and pollution problem throughout the world (Kwon et al., 2015; Martínez et al., 2013). As tyres are designed to be resistant to physical, chemical and biological degradation, they cannot self-decompose in normal atmospheric conditions (Martínez et al., 2013; Sienkiewicz et al., 2012). Illegal open dumping provides an ideal living environment for mosquitoes, viruses and insects, which leads to a serious hygiene issue and poses a threat to human health. The stockpiling of waste tyres may cause accidental fires which are difficult to extinguish as the calorific value of tyres is very high. The fires generated also cause serious pollution to the environment due to the release of a great amount of volatile organic materials (Manchón-Vizuete et al., 2004) and toxic substances, such as SO_x and NO_x (Shakya et al., 2008). Therefore, it is important to find a proper method for the handling of waste tyres.

One common waste tyre management option is landfilling in which scrap tyres are shredded into smaller pieces and then dumped into a landfill site. Although it is a simple disposal method, this route is being discouraged due to resource wasting, the cost of shredding as well as the limited amount of available landfill space (Chang, 2008; Hadi et al., 2014b, 2013d; Shu and Huang, 2014).

Incineration, as another waste management method, can recover the high calorific value of waste tyres, but this option may produce secondary pollution without any resource recovery (Galvez-Martos and Schoenberger, 2014; Hadi et al., 2013a; Önenç et al., 2012; Siva et al., 2013). Similar criticisms apply to the use of this waste stream as an energy source in a cement kiln. Conesa et al. have analyzed the gaseous emissions from a cement kiln pilot plant and reported that the emissions of polycyclic aromatic hydrocarbons (PAHs) and dioxins increased with the amount of tyre fed to the kiln (Conesa et al., 2008).

Pyrolysis is the thermal processing of materials in the absence of

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air. Pyrolysis of plastic scrap materials is regarded as a waste treatment process, which can be ecologically responsible as well as profitable as a means of recycling both energy and material (Fernández et al., 2012; Rodriguez et al., 2001). Pyrolysis of waste tyres produces pyrolytic oil, non-condensable gas and tyre char (Antoniou et al., 2014; Choi et al., 2014; Fernández et al., 2012; Rodriguez et al., 2001). The pyrolytic oil may be used directly as fuel or added to petroleum refinery feedstock (Cunliffe and Williams, 1998; Hooshmand Ahoor and Zandi-Atashbar, 2014; Laresgoiti et al., 2004; Murugan et al., 2008; Quek and Balasubramanian, 2013). The non-condensable gas, with a heating value similar to natural gas, can also be used as fuel (Fernández et al., 2012; Laresgoiti et al., 2000). The tyre char can be used as smokeless fuel or as a raw material in the production of carbon black (Alexandre-Franco et al., 2011; Shah et al., 2006). Due to the similar composition of tyre with some plastic materials, many studies have been devoted to the co-pyrolysis of plastic wastes and tyre rubber (Bernardo et al., 2012; Miranda et al., 2013; Navarro et al., 2012; Saraf et al., 1995). But one disadvantage of the pyrolysis of waste tyre is that the overall financial revenue of the products cannot overcome the high operating and energy cost of the pyrolysis process and as a result, the process is considered as uneconomical (Jang et al., 1998; Martínez et al., 2013).

Tyre char, as a rich carbon source, has been widely used as a potential precursor for the production of value-added porous adsorbent materials for environmental remediation purposes (Fuente-Cuesta et al., 2012; Manchón-Vizuete et al., 2005; Tomei and Daugulis, 2013). This can add great value to this low-cost material and also have dual-environmental benefits (Portofino et al., 2013). One of the main challenges in tyre char activated carbon preparation is the high amount of energy used in this process. Increasing the degree of activation usually enhances the porous structure of the produced activated carbons, but at the same time, reduces the carbonaceous adsorbent yield due to higher carbon burnoff. Considering these two opposing phenomena, in this study, “yield-normalized surface area” has been introduced which is defined as the surface area of the activated carbon for unit weight of the unactivated material. This term takes the yield of the carbon into consideration and thus gives a more realistic prediction of the optimum activation conditions.

2. Material and methods

2.1. Raw material

Tyre char containing 85 wt% carbon was provided by Global Power and Energy Company Limited (Global Green) which operates a waste tyre pyrolysis pilot plant in Dongguan, China. Scrap tyres are de-treaded and the waste tyre is converted into fuel gas, hydrocarbon fuel and tyre char in a fixed bed pyrolysis reactor at an average temperature of 450 °C.

2.2. Activation studies

Before commencing the activation process, nitrogen (N_2 with a purity of 99.7 v/v%) with a flowrate of 200 ml/min was purged into the furnace for an hour to remove any air in the heating chamber. Approximately 30 g tyre char was loaded into the furnace and heated at a rate of 15 K/min under a nitrogen atmosphere until the desired temperature, ranging from 900 to 975 °C, was achieved. When the target activation temperature was reached, steam and nitrogen (85:15 v/v) as activating agent with a total flowrate of 700 ml/min were injected into the activation chamber by a peristaltic pump. The activation process was performed for a range of activation durations, 2–6 h, to create various porous structures.

2.3. Elemental analysis

An elemental analyzer, model ELEMENTAR VARIO EL III, was used to determine the mass fractions of the carbon, hydrogen, nitrogen and sulfur contents (in weight %) of the tyre char. The carbonaceous material was exposed to a temperature of 1000 °C under an oxygen atmosphere. The produced gases (CO_2, SO_2, N_2 and H_2O) were separated in chromatography columns and then measured by highly selective infrared (IR) and thermal conductivity detectors.

2.4. Proximate analysis and ash content

The moisture content (in weight %) was investigated by using a moisture balance, model OHAUS MB45. Fixed carbon and volatile organic matter contents (in weight %) were investigated following the ASTM 5832 method, called Standard Test Method for Volatile Matter Content of Activated Carbon Samples. The volatile matter content was obtained as a mass loss when heating the sample under 950 °C for 30 min. The mass left was defined as a combination of fixed carbon and ash content. Ash content was tested using the ASTM D2866 method, called Standard Test Method for Total Ash Content of Activated Carbon. The sample was heated to 650 °C with air until a constant sample weight was obtained.

2.5. Calorific value

The samples were first dried at 105 °C to remove any moisture. The calorific value of tyre char (in joule per gram) was investigated using an oxygen bomb calorimeter, the PARR 6100. Benzoic acid was employed as standard material for the calibration of the calorimeter under specified conditions. The tyre char sample was placed in a crucible and oxidized under a pressure of 30 bar oxygen.

2.6. Thermal analysis

The weight loss of tyre char as a function of temperature was determined by an analytical technique, namely thermogravimetric analysis, using a model TGA/DTA Pyris 1 instrument. Approximately 10 mg sample was placed into a platinum crucible attached to a precise microbalance, heated to the prescribed temperature at a specified heating rate in the furnace in a controlled ultra-pure nitrogen atmosphere. For each sample, at least three trials were conducted to ensure the results are consistent.

2.7. Nitrogen gas adsorption–desorption

The textural characterization of the original and activated materials was conducted using an automated volumetric gas adsorption apparatus, model Autosorb-I, Quantachrome. Adsorption and desorption of N_2 was performed at 77 K. Before analysis, all carbon samples were outgassed at 473 K for 6 h under a vacuum condition.

The obtained adsorption–desorption data were then analyzed to obtain the BET surface area using the Brunauer-Emmet-Teller (BET) equation (Brunauer et al., 1936), micropore volume and external surface area by the t-plot method (Lippens and de Boer, 1965) and pore size distribution using the Barrett-Joyner-Halenda (BJH) method (Barrett et al., 1951).

3. Results and discussion

3.1. Tyre char properties

The physical properties of the tyre char have been summarized in Table S1. A more detailed discussion of the properties of the tyre