Resources, Conservation & Recycling 124 (2017) 67–73

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Eco-design for recycled products: Rejuvenating mullite from coal fly ash

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ARTICLE INFO

Keywords:
Eco-design
Industrial solid waste
Material products
Coal fly ash
Mullite

ABSTRACT

Secondary pollution exists extensively in the utilization of industrial solid waste. To reduce environmental risks of building material products recycled from industrial solid waste, a framework of eco-design strategy is established based on the existing eco-design method and life cycle thinking. It focuses on controlling of chemical components by integrating tracking and controlling of toxic components introduced by industrial solid waste. The framework consists of four steps: analysis of raw material applicability, analysis of process control conditions, and safety analysis during product use and final disposal. Raw material requirements are designed including effective components, quality disturbance components, and environmental risk components. Operating condition requirements are given to control flows of selected components in key procedures. Environmental safety of products during use and final disposal under these requirements are tested by simulation experiments. Then a series of eco-design requirements are proposed. The framework is applied in a case study of mullite recycled from coal fly ash and the result shows that the established framework could be feasible for products recycled from industrial solid waste. Nevertheless, the method needs expansion with industrial solid waste properties and product requirements, and steps need optimization if applied in other wastes.

1. Introduction

General industrial solid waste is a main part of industrial solid waste, such as fly ash, gangue, and steel slag (Liu et al., 2016). It contains different chemical components, like SiO_2 and Al_2O_3 (Vassilev et al., 2013). Enormous industrial solid waste has occupied a lot of land and caused many serious environmental problems. Many studies have focused on synthetic technologies of raw material from industrial solid waste to effectively utilize resources and solve the environmental problems (Siddique, 2009; Singh and Siddique, 2013), especially synthesis of industrial raw materials or building materials, such as zeolite, alum, mullite and cement (Kourti and Cheeseman, 2010; Yang et al., 2010). Comprehensive utilization is still a main way in China to deal with general industrial solid waste.

Meanwhile, secondary pollution exists extensively in utilization of general industrial solid waste, especially the pollution caused by toxic components in industrial solid waste. Toxic components, like heavy metal pollutants, would bring environmental risks by direct release into environment in recycling or accumulation in products. The problems have been discussed by several authors. Yu et al. (2014) shown heavy metal flows in utilization of coal fly ash and found that coal fly ash is a main source of heavy metals. He et al. (2013) reported leaching characteristics of metal elements from flue dust of copper scrap smelting. Cetin et al. (2012) and Cetin and Aydilek (2013) focused on leaching behavior of trace metals from fly ash which was applied in highway construction. At present, these researches still have some limitations: 1) pay more attention to detection of contaminants instead of pollution prevention and control in production; 2) environmental risks of toxic components accumulated in recycled products have been not studied.

Aiming at these limitations, pollution control of toxic components throughout a product's life cycle is needed. Eco-design is an approach that integrates "environmental aspects into product design and development" at all phases of a product's life cycle (ISO, 2011; ISO/TR, 2002). It considers the entire life cycle of a product with an understanding of overall process steps and is useful to reduce potential environmental risks. Therefore, eco-design is introduced in this research for improvement of utilization technology of general industrial solid waste.

A substantial amount of research on eco-design methods and tools has been performed and a series of achievements are made in the last years (Casamayor and Su, 2013; Rossi et al., 2016; Santini et al., 2010), such as life cycle thinking and Eco-design Pilot. Life cycle thinking considers environmental risks of the entire life cycle and proposes

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http://dx.doi.org/10.1016/j.resconrec.2017.04.005
Received 3 December 2016; Received in revised form 6 April 2017; Accepted 7 April 2017
Available online 03 May 2017
0921-3449/

corresponding eco-design strategy (Bonou et al., 2015; Pelletier, 2015). Eco-design Pilot is a very useful online tool and its specific steps are as follows: characterize the product and ascertain those phase of life cycle showing the main environmental impact; list a number of appropriate eco-design checklists; find concrete and realizable measures for product improvement. A eco-design strategy is typical outcome of eco-design methods and tools to reduce environmental risks (Baran et al., 2011; Mirabella et al., 2014).

Presently, eco-design method and strategy are usually applied in terminal products, such as production (Alonso Movilla et al., 2016; Bonou et al., 2016; Favi et al., 2012) and recycling or remanufacturing of electronic displays (Ardente et al., 2014, 2015; Krystofik et al., 2015), because they are more accessible to the ordinary consumers and significantly affect human health. As the industrial raw materials of terminal products, material products also need the guidance of eco-design to reduce environmental risks in an interconnected industrial system. At present, several researchers explore the eco-design of general building materials (Medina et al., 2016; Proske et al., 2014; Tonelli et al., 2016), whereas few explore the eco-design of material products recycled from industrial solid waste.

Given the vast storage volume in China, recycling industrial solid waste for building materials and other material products is encouraged. Products recycled from industrial solid waste are widely used in many fields, especially in the construction of buildings and houses. In this context, the existing eco-design strategy that recommends the use of low toxic natural raw material (Ribeiro et al., 2013; Van der Velden et al., 2015) is insufficient to control environmental risks caused by the raw material itself. Therefore, it is necessary to expand eco-design method to the field of material products recycled from industrial solid waste to reduce environmental risks and ensure the safety of recycling products.

Referring to the existing eco-design method and strategy, the researchers present a framework of eco-design strategy for material products recycled from industrial solid waste. The framework focuses on chemical components and establishes an approach to track and control toxic components carried by industrial solid waste. The framework introduces substance flow analysis into operating condition analysis of recycling technology and process. The eco-design framework is applied in eco-design of mullite recycled from coal fly ash.

2. Methods

Eco-design strategy includes a range of approaches designers can use to improve environmental performance of products at every life cycle phase. Life cycle phases of products span from raw material acquisition through production, use and final disposal. The right combination of the approaches throughout the life cycle can help to develop a well-designed and environmentally responsible products. Based on life cycling thinking, characteristics of products recycled from industrial solid waste are analyzed.

Products recycled from industrial solid waste have the following characteristics: first, toxic components in industrial solid waste do harm to environment and reduce product quality; second, industrial solid waste is mainly recycled for industrial raw materials and building materials, quality of which is closely related to chemical components (Ahmaruzzaman, 2010; Yao et al., 2015); third, raw material is usually produced by process industry, and it is closely related to chemical components distribution and process conditions (Yin, 2009).

According to the characteristics, eco-design framework of products recycled from industrial solid waste was designed based on the traditional method of eco-design products (Wimmer and Züst, 2003; Wimmer et al., 2004) and the steps of eco-design founded by Vienna University of Technology (TU wien, 2017), as shown in Fig. 1. The core goal of the method is to control the toxic components and products use and final disposal.

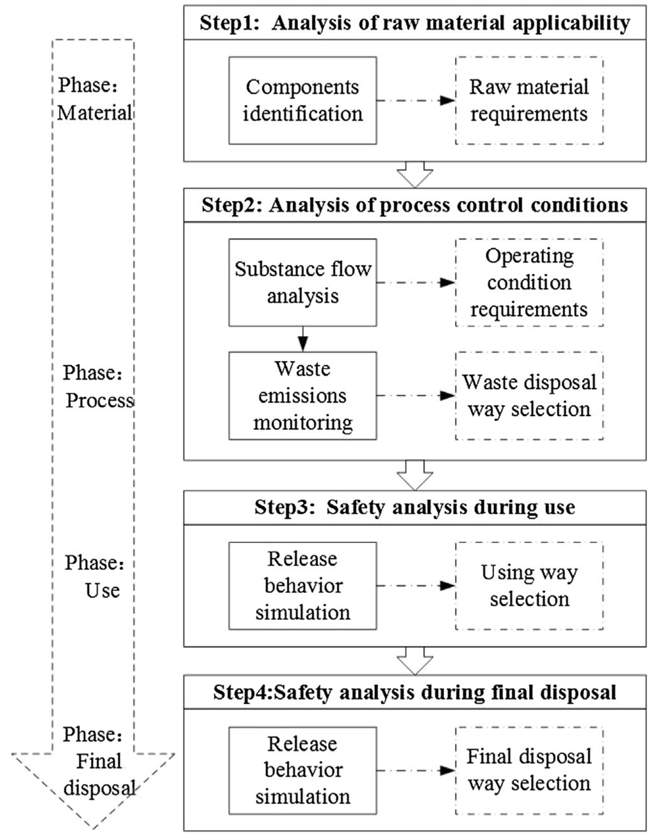

Fig. 1. Framework of eco-design strategy for products recycled from industrial solid waste.

(1) Analysis of raw material applicability

An analysis of raw materials applicability is highly important in product eco-design, given that the raw materials are main sources of pollution in the whole production. Eco-design strategy for terminal products usually recommends using cleaner or the most appropriate natural materials with low toxic components to reduce environmental risks from the source, which is not applicable for industrial solid waste with toxic components.

Considering that chemical components of industrial solid waste are complex and tend to fluctuate, the eco-design strategy for material products needs to meet product quality requirements and control environmental risks of toxic components as much as possible. Chemical components of raw materials are selected and divided into three groups on the basis of product requirements: effective components, quality disturbance components and environmental risk components. Product quality requirements are confirmed by international or national product standards. The fluctuation ranges of the selected components are analyzed and raw material control requirements is presented.

(2) Analysis of process control conditions

Process control is a key approach to achieve product eco-design. For most terminal products, eco-design strategy involves production optimization during process control and monitoring of waste emissions during production. However, it is difficult to implement process control for products recycled from industrial solid waste. Industrial solid waste is recycled for material products by process industry. The optimization of a separate module or reactor could not control chemical components of raw materials comprehensively, thus substance flow analysis is introduced to control components overall (Long et al., 2013).