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Recycling difficult-to-treat e-waste cathode-ray-tube glass as construction and building materials: A critical review

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ABSTRACT

Cathode ray tubes (CRTs) waste generation has become a great environmental challenge worldwide. CRT glass possesses reasonable intrinsic strength, low water absorption and rich in silica, which makes the glass suitable for use as sand or pozzolan in construction materials. This work presents a comprehensive overview of literature reporting on the reuse of CRT glass to prepare glass-ceramics; cement mortar, paste, and concrete; and bricks. The effects of various critical factors on the resulting products' performance, preparation mechanisms, leaching behavior, lead fate, and environmental and human safety were investigated. The comparison of these recycling methods, and directions for future research were discussed and reported as well. Preparing cement mortar, paste, and concrete from CRT glass offer added advantages in terms of quantity of recyclable cathode ray tube glass at a given time, with minimal environmental and economic implications and thus could be an a promising value-added uses for CRT glass. The geographical distance between waste CRT glass sources and processing facilities, public policies should be taken into account in its recycling.

1. Introduction

The management and treatment of electronic waste (e-waste) has create a global environmental challenge, due to its rapidly growing volume and complex (or hazardous) nature. A report from "The Global E-waste Monitor 2014: Quantities, flows and resources" released by the United Nations University revealed that a total of an epic 41.8 million tons of e-waste was generated worldwide in 2014 [5,82]. In recent years, the replacement of cathode ray tube (CRT) sets with liquid crystal displays (LCDs), light-emitting diode (LED) panels and plasma display panels (PDPs) is dramatically progressing, producing millions of units of waste CRTs. Data from the waste electrical and electronic equipment (WEEE) collection and pretreatment market indicate that approximately 50,000–150,000 million tons/year of end-of-life CRTs are currently collected in Europe, and this volume is not expected to decrease for coming several years [2]. In China, the recycling and dismantling amounts of waste electrical appliances (including TVs, refrigerators, washing machines, air conditioners, and personal computers) reached 41.499 million units in 2013, of which around 92% were TV CRTs. The bulk of a CRT consists of glass parts (including funnel, panel and neck glass), typically representing 85% of the total weight of monitors (Fig. 1). In the UK alone, more than 100,000 t of CRT glass have been disposed of annually since 2003 [36]. Globally, it is estimated that only about 26% of the discarded CRTs are recycled and the remaining 59% are landfilled due to less practical recycling approaches [65]. The panel made of barium-strontium glass, the funnel made of lead silicate glass containing approximately 20 wt% PbO and neck glass 40 wt% PbO [84,85]. Strong concerns have been raised about the potential of toxic-metal leaching from CRTs [34,75]. Therefore, there is a pressing need to develop effective recycling methods for these difficult-to-treat e-waste products.

In general, there are two principal approaches of recycling CRT glass: closed-loop and open-loop recycling. In the closed-loop recycling, CRT glass is generally reused as raw material to manufacture new CRT monitors. For this recycling, it could be profitable only in the case of an absolute separation of the lead-containing and lead-free glass [32]. With the rapid shrinking of demand for new CRTs, most CRT manufacturers have gradually ceased or restructured the funnel manufacturing facilities of their CRT operations. Therefore, a dramatic drop in closed-loop recycling has occurred, and attention has shifted to open-loop recycling [58,60].

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Fig. 1. The generation of CRT glass.

2. Construction and building materials

CRT glass possesses reasonable intrinsic strength, low water absorption and rich in silica, which makes the glass suitable for use as sand or pozzolan in construction materials. Accordingly, a number of projects have been undertaken to use CRT glass for the production of foam glass, ceramic-glaze, cement and concrete. There has been considerable research focuses on the feasibility of applying these recycled CRT wastes in the field of construction and building materials. However, to the best of our knowledge, there are sparse comprehensive reviews undertaken on this important topic except of the work of Rashad [66], Iniaghe and Adie [33]. Hence this paper presents a thorough overview of the literatures reporting on the reuse of CRT glass to prepare glass-ceramics; cement mortar, paste, and concrete; and bricks (Fig. 2). The effects of various critical factors on the resulting products' performance, preparation mechanisms, leaching behavior, lead fates, and environmental and human safety were analyzed. The comparison of these recycling methods, and directions for future research, were discussed and reported as well.

2.1. Foam glass-ceramic

Because of its excellent intrinsic properties—such as low thermal conductivity, low water absorption and incombustibility—foam glass has attracted growing attentions, and has been applied in various fields, such as building and road construction, the petroleum and chemical industries, underground engineering, and military defense [16,30]. From its physical aspect, foam glass is a porous thermal and acoustic-insulating material with high true porosity of up to 90–97%. It is a heterophase system, consisting of vitreous solid and gaseous phases. In the first phase, solid glass forms thin walls of single cells, which are filled during the second, gaseous, phase [76]. Foam glass is generally produced with a powder method [67] consisting of mixing and sintering a mixture of glass cullet and foaming agents. When it is heated above the softening point, the solid glass becomes a viscous liquid, and the decomposition or oxidation of foaming agents lead to the formation of bubbles, which are trapped within the melt. The expanding gas bubbles increase the sample volume, thus forming a typical porous product [37].

2.1.1. Effects of glass cullet

Foam glass is mainly produced from different types of glass cullets, such as flat glass, container glass, and cullet derived from discarded TV sets and computers, as well as the luminescent lamp glass. However, it can also be fabricated from other glassy materials, such as fly ash and slag. Recently, extensive studies have been carried out to use CRT glass (single funnel, panel glass or a mixture of these) for making foam glass (Table 1). Bernardo and Albertini [7], König et al. [38], Petersen et al. [62], and Mucsi et al. [59] fabricated foam glass by using CRT panel glass and different foaming agents (carbon, sodium carbonate and calcium carbonate). Guo et al. [30] and Méar et al. [54] used funnel glass with SiC and TiN as foaming agents to prepare foam glass. [51] and Fernandes et al. [26] also prepared foam glass from a mixture of funnel and panel glass with SiC, TiN, egg shells, calcite and dolomite as foaming agents. The weight ratio of panel and funnel was found to affect the foaming behavior and consequently the product properties. Both panel and funnel glass consist of similar contents of modifier oxides (Na_2O + K_2O + CaO + MgO), whereas funnel glass presents a lower content of silica than of panel glass. In addition, funnel glass is rich in lead while panel is a barium-rich glass. The distinction between their chemical compositions results in different thermal behaviors. In fact, the glass should attain low enough viscosity (10^7–10^8 poise) for