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Characterization of the non-metal fraction of the processed waste printed circuit boards

Amit Kumar [a,*], Maria E. Holuszko [a], Travis Janke [b]

[a] NBK Institute of Mining Engineering, University of British Columbia, Vancouver, BC, Canada
[b] Ronin8 Technologies Limited, Richmond, BC, Canada

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ABSTRACT

Electronic waste is one the fastest growing waste streams in the world and waste printed circuit boards (PCB) are the most valuable part of this stream due to the presence of gold, silver, copper, and palladium. The metal present in PCBs is mostly recovered for the market value whereas the nonmetal fractions are often ignored. This research explored the characteristics of the non-metal fraction (NMF) obtained after the processing of milled waste PCBs with a focus on responsible end-of-life solutions, in the form of non-hazardous landfilling or incineration. The NMF was characterized using sizing, assaying, loss on ignition, calorific value measurement, and thermogravimetric analysis (TGA).

The result showed that the metal content in the NMF increased with decrease in the particle size for most of the metals except antimony and the result from loss on ignition (LOI) also showed that over 50% of the coarser fraction represented organic matter compared to less than 30% for the finest fraction. The study also showed that after the recovery of metals from the waste PCBs, landfill leaching for most of the metal is reduced below the environmental limits, with lead being the only exception. The lead leachate concentration of 18 mg/L was observed, which requires further treatment prior to landfilling. With an energy value of 16 GJ/t, the NMF could provide high energy recovery if incinerated but 194 mg/kg of hazardous flame retardants present in the NMF might be released if the combustion process is not closely monitored.

1. Introduction

E-waste is one of the fastest growing waste streams in the world in terms of volume and its subsequent environmental impact on the planet. Balde et al. (2015) estimated that the total e-waste generated worldwide was 41.8 million tonnes in 2014 (5.9 kg/inhabitant). The total e-waste produced by Canada was 725 kt in 2014. The e-waste generated per capita was 20.4 kg. The global growth rate for e-waste stream is 3–5% (Cucchiella et al., 2015) and expected to reach 50 million tonnes worldwide by 2018 (Balde et al., 2015). This e-waste stream provides an economic opportunity if recycled due to the presence of valuable metals such as copper, silver, gold, and palladium. Namias (2013) showed the presence of 60 different elements in e-waste. The total value of the e-waste stream is estimated at 40 billion Euros (Balde et al., 2015).

The waste printed circuit boards (PCB) represents a significant portion of this value, accounting for over 40% of the total e-waste metal value (Golev et al., 2016). Quantitively, almost 6% (w/w) of the total e-waste is printed circuit boards, which contain a significant amount of valuable metals (Evangelopoulos et al., 2015). The metal concentration in waste PCB is approximately 20% (by mass) of copper, 1000 ppm of silver, 250 ppm of gold and 110 ppm of palladium, compared to 0.6% (by mass) of copper, 215 ppm of silver, 1 ppm of gold and 2.7 ppm of palladium for an average mine (Desjardins, 2014; Kumar et al., 2017; Namias, 2013). The potential revenue from waste PCB is estimated to be $21,200/t (Cucchiella et al., 2015).

There are several types of PCBs, such as FR-2 to FR-6, CEM-1 to CEM-8, and G-10 and 11. The core of these PCBs are comprised of multiple layers of reinforcing laminate sheets, where epoxy, phenolic, and polyester are the major resins, and cellulose, woven glass, and mat glass are the major reinforcement materials. For example, FR-2 is cellulose reinforced with phenolic resin, FR-3 is cotton paper reinforced with epoxy resin, FR-4 and 5 are glass fiber reinforced with epoxy resin and FR-6 is mat glass reinforced with polyester resin. FR 1, 2 and 4 is used where flame retardancy is required, FR-3 have higher insulation resistance, FR-5 have higher thermal stability and FR-6 is useful for high-impact applications (Weil and Levchik, 2004).

* Corresponding author.
E-mail address: amit9937@mail.ubc.ca (A. Kumar).

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The two most commonly used PCBs in electronics are FR-2 and FR-4. FR-2 is used in low-end electronics such as televisions and radios, whereas FR-4 is used in high-value electronics such as cellphones and laptops (Guo et al., 2009; Marques et al., 2013). The metals present in the PCBs are extracted for its value and the remaining non-metal fractions (NMF) containing the resins, reinforcing materials, and residue metals are often sent to landfills (EPA, 2012).

The NMF accounts for almost 70% of the PCB mass (Veit et al., 2014; Zheng et al., 2009). Several studies suggested that the NMF consisted of glass fiber (65% by wt.), cured epoxy resin (32% by wt.) and impurities (copper: <3%, soldering alloys: <0.1%) with the highest glass fiber and copper concentration in the fine fraction, and the highest resin concentration in the coarse fraction (Guanghan et al., 2016; Marques et al., 2013). Muniyandi et al. (2014) showed that the NMF obtained from PCB processing contains SiO_2 (43%), CaO (19%), Al_2O_3 (9%), Br (4%), CuO (6%), Fe_2O_3 (0.8%), MgO (0.6%), BaO (0.5%) and other metals and metal complexes such as TiO_2, SrO, SnO_2, ZrO_2, ZnO, NiO, PbO in smaller quantities. Duan et al. (2016) used X-ray Fluorescence (XRF) to show the presence 0.2–8% Cu, 0.03–0.8% Pb, 0.1–0.55% Sn, 0.01–0.0% Ni, 0.01–0.02% Zn, 0.02% Mn and 0.01–0.02% Cr in the NMF obtained after separating the copper.

According to the Environmental Protection Agency (2012), the recycling of NMF from waste PCBs is not usually practiced, and up to 94% is discarded in landfills. Most researchers suggest direct use of the NMF as secondary substitution materials such as a filler for construction materials, paint, decorating agent, adhesives, insulating materials or production of non-metallic plates to produce composite boards (Sohaili et al., 2012). Guo et al. (2009) listed four ways to recycle the NMF by chemical methods. These are pyrolysis, gasification, supercritical fluid depolymerization, and hydrogenolytic degradation with the primary goal of converting the polymers in the NMFs into chemical feedstocks or fuels. Physical separation of individual components of NMF is more complicated than the chemical treatment due to the complex structure and encapsulation.

Research in the field of characterization of the NMF and associated risks with its reuse or disposal are limited (Duan et al., 2016). A concentration of 6–12% of bromine and 0.02–1% of chlorine has been reported by Duan et al. (2016) in the NMF obtained from FR-2, FR-3, and FR-4. The concentration of polybrominated diphenyl ether (PBDE) in waste PCB is reported to be 3045 mg/kg (Zhou et al., 2013) whereas the concentration in the NMF after the processing is not available in the literature. Similarly, landfill leaching analysis from milled waste PCB shows the presence of 133 mg/L Pb and 22 mg/L Cd (Bizzo et al., 2014) whereas leaching characteristics for the NMF has not been reported. Guanghan et al. (2016) suggested that NMF doesn't decay for a long time and it also reduces the air permeability of the soil and pollutes the groundwater due to the presence of heavy ions and curing agents. Bizzo et al. (2014) separated the metal and non-metal fractions using organic liquid at a density of 2.89 g/cm^3 and showed that the NMF had a gross calorific value of 11.63 GJ/t compared to 4.88 GJ/t for the whole waste PCBs. The PCBs used for this test were ground in a cutting mill to a size of 80% passing at approximately 3600 μm.

The available literature showed that the characterization study in terms of metal analysis, landfill leaching, and PBDE analysis are limited to waste PCBs. Some available researches were performed on NMF separated in the laboratory at specific densities, but a comprehensive characterization study has not been performed on the NMF fraction. This paper presents a thorough evaluation of the characteristics of the NMF with respect to the relevant environmental and quality standards for determining potential responsible end-of-life solutions. Similar information for waste PCBs prior to any processing or beneficiation is available in literatures. However, the majority of waste PCBs are processed in some fashion prior to disposal consequently, a characterization study for the separated nonmetal fraction is more appropriate for evaluating characteristics for applicable end-of-life solutions. The NMF was obtained from an industry partner processing printed circuit boards at a large scale. The characterization study was performed using various tests such as toxic leaching test, thermogravimetric analysis, calorific value test and assaying. The paper discusses the outcomes of this study in order to determine a responsible end-of-life solution for the NMF fraction.

2. Materials and methods

2.1. Material

Approximately 25 kg of air-dried NMF was sampled from the processing plant located in Richmond, British Columbia owned by Ronin8 Technologies Limited. The plant process a mixture of FR-2 and FR-4 PCBs obtained from computers, printers, and televisions. The crushed printed circuit boards are processed using gravity separation (wet concentration table) to separate metals from non-metal. The obtained sample was dried at 60 °C for 96 h in an oven manufactured by Estrin Industries, model number 100-00, serial number 18626. The dried samples were split to obtain subsamples for subsequent test works.

2.2. Equipment and test procedures

2.2.1. Particle size distribution analysis

Two subsamples of approximately 300 g were split from the dried sample to perform the particle size distribution using screening for 20 min. A Ro-Tap machine manufactured by W.S. Tyler, model number RX-29, serial number 10-5557 was used for this analysis. The size distribution was plotted, and 80% and 50% cumulative passing size were determined.

2.3. Metal assay

Approximately 20 g of subsamples were split using the Riffle splitter from the received NMF and each size fractions obtained after screening were sent to an external laboratory for metal assay using standard procedures, EPA200.2/6020A for metals and EPA200.2/1631E for mercury. A sample of the as-received NMF was also sent for analysis.

This procedure is designed to determine total recoverable elements from water and solid, with the exception of silica (EPA, 1994). The limitation of the process is that some of the metals might be embedded in the silica matrix of the printed circuit boards that would not be digested. The samples are screened at 4000 μm (5 mesh) and any coarse fraction is ground using a mortar and pestle. From the dried ground sample, 1 ± 0.01 g of a sample is obtained and digested in 4 ml HNO_3 and 10 ml HCl in a beaker at 95 °C for 30 min. The solution is then centrifuged to obtain a clear solution which is then analyzed by inductively coupled plasma-atomic emission spectrometry (ICP-AAS).

2.3.1. Loss on ignition measurement

The loss on ignition was performed using a muffle furnace manufactured by Vcella Kilns, Inc. Model 13, serial number 5050. Approximately 1 g sample from each size fractions was heated from room temperature to 750 °C in the presence of air and left for roasting for 3 h. Most of the volatile matters were burnt off, and the remaining mass was weighed to estimate the weight loss (loss on ignition) during the process. This test was performed in