ÁREA TEMÁTICA: RECICLAGEM

PHYSICAL PROCESSING AND ANALYSYS OF MATERIALS CONTENT OF SMALL-SIZE WASTE ELECTRIC AND ELECTRONIC EQUIPMENT (WEEE): A CASE OF SMARTPHONES PRINTED CIRCUIT BOARDS

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ABSTRACT
Due to a wide variety of components, cell phones are some of the most complex electronic devices. Indirectly, technological advancements cause negative environmental impact due to the disposal of obsolete cell phones. One of the ways to minimize such impact is the recovery of materials. This study analyzed the recovery of metals from smartphones, especially in printed circuit boards (PCBs), using physical processes. The devices collected were manually disassembled, PCBs components were removed by thermal processing and ground in a knife mill. Five fractions of different grain size ranges were then separated by sieving. The material was analyzed by X-ray fluorescence, inductively coupled plasma mass spectroscopy (ICP-MS), and thermogravimetric analysis. The main components of smartphones were polymers (28%), battery (23%), display (19%), PCB (17%), others (10%), and small metal parts (3.5%). After milling, 48% wt. of PCBS were observed in the grain size fraction between 1 and 2 mm, which included the highest amount of Cu, Fe, Al, Sn, Pb, and Ni. Mechanical processing was efficient to recover metals like copper (22.4%) and tin (1.04%), which were the most abundant metals in cell phones, as observed by ICP-MS. Over 50% of the fractions analyzed was composed of copper, making smartphones an interesting source of materials, in addition to other metals that may be recovered. Toxic metals like Cd and Pb are present in PCBs of the smartphones analyzed, underscoring the importance of appropriate treatment for this kind of waste to prevent environmental impacts.
Palavras-chave: Recycling; Smartphones; Recovery.

1. INTRODUCTION

Due to programmed obsolescence, the fast pace of technological innovation, and increased consumption, electronic devices are replaced quite often and become technological waste within a rather short period of time (SILVA et al., 2017; BABAYEMI et al., 2017). When obsolete, these materials end up being disposed of together with common waste and since their composition includes several heavy metals, they may cause considerable environmental impact (SILVA et al., 2017). The economic relevance at global level and the overall improvement they mean to society are clear benefits of cell phones, although the end-of-life management of these products in developing countries has not been given due attention concerning sustainability (ROBINSON, 2009; BABAYEMI et al., 2017; PÉREZ-BELIS et al., 2014). Research has shown that disposed cell phones are the kind of waste that grows fastest worldwide (ROBINSON, 2009; PÉREZ-BELIS et al., 2014; BABAYEMI et al., 2017).

According to a 2015 report issued by the United Nations Environment Program (UNEP), the electronic industry generated 41 million tons of electronic waste from computers and smartphones, and it is estimated that this number will reach 50 million tons in 2018 (PNUMA, 2017). A study estimated that 1.4 million tons of waste electrical and electronic equipment (WEEE) are generated per year in Brazil alone (ARAÚJO et al., 2015). This concern has prompted the introduction of regulations across the globe, like the Restriction of the Use of Certain Hazardous Substances (RoHS) incentive, since the European industry had to adapt products removing lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr(VI)) and other hazardous substances. Besides stricter international regulations, the constant increase in WEEE points to the need for the development and improvement of processes to recover materials and to make the electronics industry sustainable (SILVAS et al., 2015). The Brazilian Policy for Solid Waste (federal law number 12305) binds manufacturers, importers, distributors, and points of sale of electronic equipment to implement reverse logistics systems (BRASIL, 2010).

Containing hazardous materials like Pb, Hg as well as polybrominated biphenyls, WEEE are chemically very distinct from urban or industrial solid waste (Echegaray and Hasstein, 2016). On the other hand, this kind of waste also contains rare and valuable materials that may be recovered using appropriate recycling methods in order to remove hazardous materials and avoid environmental and health problems, highlighting not only the economic importance but the environmental relevance of recycling cell phones (IŞILDAR et al., 2018; LI et al., 2017). However, the prevailing trend is to consider WEEE as urban solid waste, requiring disposal as such.

According to the Brazilian Telecommunication Agency (ANATEL), in 1990 there were 667 cell phones in the country. Other studies have shown that by September 2017 this number reached 242.1 million devices, meaning 115.93 cell phones per 100 inhabitants, or more than one per person. It has been estimated that by 2018 Brazil will have 416 million cell phones in use (ANATEL, 2018). More specifically, the Brazilian Association of Electric and Electronic Industry (ABINEE) calculates that smartphone sales increased from 25.2 million devices in 2012 to 54.6 million in 2014 (ABINEE, 2016).

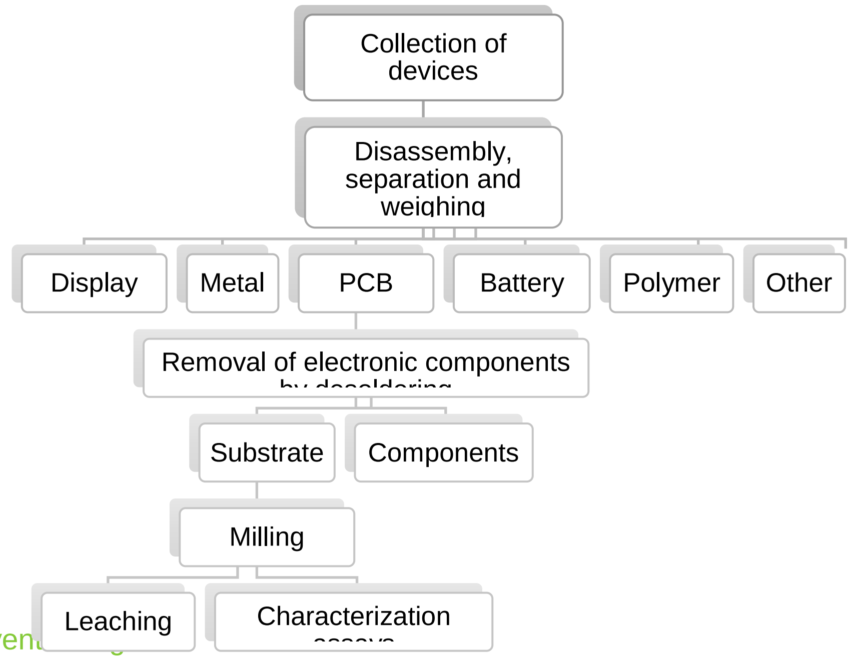
2. OBJECTIVE

In this scenario, the present study describes the dismantling, sorting, characterization and extraction of materials present in smartphones, especially the metals used to manufacture printed circuit boards (PCBs).

3. METHODOLOGY

This study was carried out in three steps: (i) collection of cell phones and identification of parts, (ii) the separation of the substrate (boards without their electronic components) and the components of PCBs, and (iii) the preparation, characterization of materials and concentration technique. The essays carried out included: (i) grain size distribution, (ii) density, (iii) X-ray fluorescence (XRF), (iv) leaching with aqua regia, (v) inductively coupled plasma mass spectroscopy (ICP-MS), (vi) thermogravimetric analysis (TGA), and (vii) differential scanning calorimetry (DSC). Fig. 1 shows the flowchart of experiments.

Figure 1. Flowchart of experiments



3.1 Collection, separation, and identification of materials

The smartphones used in this study were donated by individual users during a campaign in the University Campus and obtained from repair shops. The devices were manually disassembled and components were identified and placed in individual plastic bags that were labeled as PCB, display, battery, polymers, metals, and others (which included parts that did not meet the criteria for inclusion in other classes, like camera, buttons, composite materials, adhesives, plastics containing other materials, etc.).

3.2 Printed circuit boards

Each PCB was weighed and all components connected to the substrate were removed by hot air (500ºC) using a re-work unit (TS-2850D, Toyo). Components of PCBs were detached before milling to reduce the contamination with substrate materials such as polymers bonded to the metals. These metals have economic value and can return to the chain as metals from secondary sources.
Both the substrate and the components were weighed in an analytical balance. The items extracted from substrates were divided in nine groups, according to the categories defined by the University of California (UC SAN DIEGO, 2016): ceramic capacitors, polarized capacitors, resistors, diodes, LEDs, inductors, integrated circuits, crystals, and connectors. This classification was carried out based on visual inspection. Next, the substrates of PCBs were mechanically processed, and the components sorted as groups were prepared for characterization by XRF.
The grain size required for the characterization assays was obtained processing materials in a knife mill. Fig. 2 shows the material before and after milling.

Figure 2. Printed circuit boards before and after milling

After milling, a sample was divided to obtain two aliquots of identical weight, one used in the aqua regia leaching assay, one in the other tests.

3.3 Characterization assays

The processed materials were characterized via physical, chemical and thermal techniques.

3.3.1 Grain size distribution

Of the 271.25 g of milled PCBs, 120 g were used in the grain size distribution assay. Samples were placed in a sieve shaker, which was run for 15 min. The meshes used were made of stainless steel, measured 8” x 2” and were 3.35 to 0.053 mm in mesh size. Each sieve was emptied and any material retained in the mesh was removed using a brush. Assays were carried out in triplicate, each using 40 g of sample. The results are expressed as means of the three measurements. The analysis was conducted according to the CEMP 081 standard, issued by the Brazilian Foundry Association (CEMP, 2003).
After separation, waste was submitted to a second screening step so as to separate the material

further as the fractions required for the other assays:

$$F_1 < 0.25 \text{ mm}$$
$$0.25 \text{ mm} < F_2 < 0.50 \text{ mm}$$
$$0.5 \text{ mm} < F_3 < 1.0 \text{ mm}$$
$$1 \text{ mm} < F_4 < 2 \text{ mm}$$
$$F_5 > 2 \text{ mm}$$

The objective of studying these grain size fractions was to discover whether these metals are specifically concentrated in one of them.
This step was also carried out using a sieve shaker. After sieving, meshes were emptied and brushed to remove retained particles and thus ensure accuracy of analysis. The fractions obtained were weighed in an analytical balance.
After separation of the five fractions of the substrate, samples were submitted to density, XRF, aqua regia leaching, ICP-MS and TGA analyses, as described below.

3.3.2 Actual density

This analysis is important in this kind of study because it may indicate the main material in each phase (metal or polymer), knowing that metals have higher specific weight, compared to polymers. The test was conducted using a helium pycnometer.

3.3.3 X-ray fluorescence

XRF determines the elemental chemical composition of materials. In this study, a semi quantitative analysis was conducted, and results are expressed as percentage. The chemical analysis was carried out in an energy dispersive XRF apparatus (EDX 720 HS).

3.3.4 Aqua regia leaching

The objective of this assay was to concentrate and identify the amount of metals, polymers, and other materials in each fraction of the PCBs analyzed. The methodology used was based on Moraes (2011). Aqua regia solution was prepared using 15 mL of hydrochloric acid and 5 mL of nitric acid. One gram of a sample of each of the five fractions of ground material was added to 20 mL aqua regia in flacon tubes. The material was left to leach at room temperature (23ºC) inside a fume chamber for 24 h. Then the mixture was filtered through J Prolab 8-μm paper. The material retained in the filter paper was dried in a stove (DeLeo) for 4 h at 60ºC and weighed. Based on studies published by Moraes (2011) and Caldas et al. (2015) that report that aqua regia leaches metals but maintains polymers and other materials in the solid state, it was possible to obtain the mass of non-metallic material in samples by weighing the material on the filter. In turn, the amount of metals was obtained subtracting the weight of the retained material from the initial weight (1 g). The leachate was used in the ICP-MS analysis. The contaminated filters were properly disposed of.

3.3.5 Inductively-coupled plasma mass spectrometry

This technique affords to detect several elements, has low detection limits, and is very accurate. It is also a fast and sensitive method (SANTOS et al., 2005). The quantitative analysis is often carried out constructing analytical curves for external standards (Skig et al., 2012). The analysis was conducted in a quadrupole ICP-MS spectrometer (ICAPq, Thermo Scientific). A multi-element standard was prepared containing copper (Cu), tin (Sn), Pb, nickel (Ni), aluminum (Al), silver (Ag), zinc (Zn), and iron (Fe). Aliquots (5 mL) of the leachate were collected for each PCB sample. Next, aliquots were diluted 30, 300, 3000, and 30 000 times using ultrapure water (Milli-Q). Results were interpreted based on the least abundant isotopes of elements that undergo interference from argon, which was used as carrier gas. For the elements that are not affected by argon, the most abundant isotopes were used, as in the determination of Sn and Pb.

3.3.6 Thermogravimetric analysis

Thermogravimetry is based on the variation of weight (loss or gain) of materials due to temperature and time variations. This technique is often used in the characterization of polymers and other materials (MOTHÉ; AZEVEDO, 2009). Based on a controlled temperature protocol, it enables the evaluation of the effect of heating may have on the weight of substances (CAREVAROLO, 2013). This analysis also allows observing the weight variation of a sample due loss of water, volatile materials, and organic compounds (FERNANDES, 2015). TGA and derivative thermogravimetry were carried out in a TGA Q-50-TA instrument. The settings used included temperature values between 20ºC and 900ºC and heating rate of 10ºC/min.

4. RESULTS AND DISCUSSION

4.1 Smartphone components

Thirty-nine smartphones were collected. The devices were produced by six manufacturers, which were named A to F to build a table. It was observed that 64.10% of the devices collected belonged to manufacturers A (Samsung) and B (Apple).

The total weight of smartphones was approximately 4.3 kg, with mean weight 119 g. As for the components, mean weight of polymers was the highest (28.07%), followed by the values for batteries (22.74%), display (19.1%), PCB (17.13%), and others (10%). Metallic components presented the lowest mean weight (3.5%).

The high weight of polymers is probably due to the fact that enclosures of most smartphones are still manufactured in this material, especially by manufacturer A, which uses the polymer polycarbonate (PC). A high percent value was expected for the display module of these devices, which is larger in smartphones compared with conventional cell phones because of the touchscreen.

4.2 Printed circuit boards

For PCBs, it was observed that 47.3% of the weight is represented by the substrate and 49.78% accounts for soldered components. The preparation of substrate and components led to a loss of 2.29% in weight.

In total, the weight of PCBs for the characterization assays was 271.24 g.

It is possible to observe that the weight-based contribution of PCBs to the total weight of smartphones varied from 12% (manufacturer B) to 21% (manufacturer D). The low weight contribution of PCBs observed for smartphones from manufacturer B is associated with the different sizes of these components, in agreement with the evolution of models. The PCBs from manufacturer B, which were released in 2010, were smaller in size compared to those released in previous years, which explains why the mean weight of these components was smaller. Babayemi et al. (2017) also observed different weights of PCBs across manufacturers.

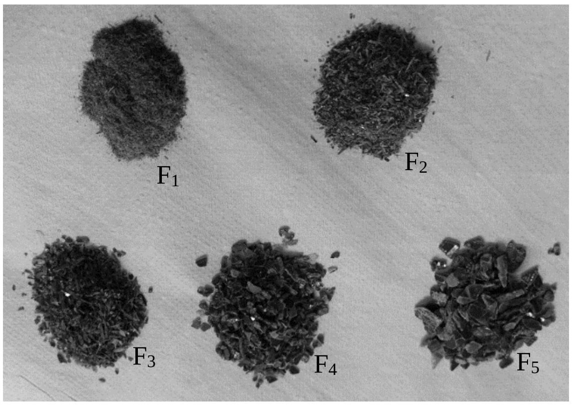
4.3 Grain size distribution

A wide variety of particle sizes was obtained, showing that the largest amounts were concentrated in grain sizes 1.7 mm and 0.85 mm, both accounting for more than 80% of the total mass.

Later, PCBs were separated in the five fractions described. The highest amount retained was 48%, in fraction 4 (1 mm < F4 < 2 mm), which is the fraction that presented the highest amount of Cu, Fe, Al, Sn, Pb and Ni, followed by 25% in the fraction whose particle size was over 2 mm (F5) followed by F3 (15.35%), F2 (5.54%), and F1 (5.51%).

The fractions obtained (Fig. 3) were submitted to characterization assays, whose results are described below. Visual inspection revealed the presence of metals in ground PCBs, indicated by shiny dots in the photograph.

Figure 3. Metals in PCBs through visual inspection



4.4 Density

The values of density of the five fractions analyzed varied little. The highest value was observed for F_2, with 3.60 g/cm^3. This value agrees with the result obtained in the aqua regia leaching assay, when the same sample had the highest amount of metals, which have higher density compared with polymeric materials.

The sample of smallest grain size (F_1) presented the lowest density (2.31 g/cm^3), indicating that this fraction possibly contains the smallest amount of metals and the highest amount of lighter materials, like polymers. Veit (2005) observed a low concentration of Cu, Ni, and Sn in a fraction of a given grain size distribution compared with fractions of larger grain sizes, indicating that metals tend to concentrate in intermediate grain size fractions.

4.5 X-ray fluorescence

Cu was the most abundant metal in all fractions that presented major elements by XRF. Babayemi et al. (2017) observed that Cu was present in 60.6% of the PCBs of the devices studied, and was detected as the most abundant metal. The studies published by Moraes (2011), Yamane et al. (2011), and Holgersson et al. (2018) reported that Cu was the element present at the highest concentrations, varying between 35% and 40%. Higher amounts of this element are typically observed in all studies, and its presence is associated with the PCB tracks, which are manufactured using this metal.

Sn and Pb are used in the soldering of PCB components and Sn was found in all fractions analyzed. The fact that they were found at smaller amounts was expected, since soldered components were removed previously to the milling of the PCB to avoid further contamination from them, though an amount must have remained on the substrate. Other elements detected at smaller amounts, like Si and Al, may be associated with the composition of fillers, since, according to Sanapala et al. (2009), silica and aluminum hydroxide are used to reduce thermal expansion and production costs.

The presence of Ni as trace element is associated with the use of the element as a film placed under the metallic contacts of keys in cell phones (YAMANE et al., 2011). The other elements observed at smaller amounts are believed to be linked with residues of components soldered on substrates, since these elements were detected in the components submitted to XRF analysis, like Fe, Br, Ac, P, Sr, and others.

Precious metals were also observed in PCBs. For example, Au was observed as trace element (<5%) in connectors, integrated circuit, and resistors, while Ag was detected in the same components as well as in the group of crystal, inductor, ceramic capacitor, and LED components. Although the literature reports increasingly rare elements like indium (In), lithium (Li), and neodymium (Nd), these were not detected by XRF in the present study. It is necessary to use a technique that does not only analyze the surface of the material and that has higher detection limits, such as ICP-MS, used for the quantification of substrate elements of PCBs.

4.6 Aqua regia leaching

Higher concentrations of metals in the leachate were observed in F_2 and F_3, with 82.42% and 51.84% of the leached weight, respectively. Both fractions have smaller grain size distributions compared

with F_4 (39.67% leached) and F_5 (39.19%), confirming the results published by Moraes (2011) in a study that observed a trend of metals to concentrate in fractions formed by smaller particles. Although fractions F_2 and F_3 presented the highest total amount of metals in the leaching assay, F_4 presented the highest amounts of the metals Fe, Al, Sn, Pb, Zn, Ag, Ni, and, mainly, Cu, which is the most economically interesting element. These elements were detected using ICP-MS. This indicates that there are other materials in the leachate that are not quantified in this study.
The highest concentration of metals observed in F_2 and F_3 was confirmed in the density test, since higher values were observed for these grain size ranges.
Moraes (2011) observed that, after milling PCBs from conventional cell phones, the highest metal content was detected in fractions above 0.25 mm in particle size, with values nearing 48% and 63% of all metal in boards. For this size range, the authors obtained 20% of polymeric and materials in a total of 37%. The values obtained in the present study are coherent, since the highest concentration of metals was observed for the fraction between 0.25 and 0.5 mm (82.42%), which decreased with increasing grain sizes.
Of the 63% of metals detected by Moraes (2011) in PCBs, 15% were present in the grain size range below 0.25 mm. In the present study, the same grain size range had the lowest metal percent content (F_1 with 24.88%). When this result is compared with the value published by Moraes (2011), it is observed that PCBs from smartphones presented high metal concentrations compared with conventional cell phones, confirming the economic potential of the recovery of metals present in this kind of waste.

4.7 Inductively coupled plasma mass spectroscopy (ICP-MS)

The results of the chemical analyses of PCBs from smartphones are presented in Table 1, which also shows the results obtained by other authors for comparison. It should be emphasized that these findings may have been influenced by the different methods used by these authors. Except for the work published by Holgersson et al. (2018), which also used smartphones, the studies cited analyzed conventional cell phones.

Table 1. Results of the quantitative chemical analysis by inductively coupled plasma mass spectroscopy (ICP-MS) compared with published findings

Author	Technique	Metal (%)							
		Fe	Al	Cu	Sn	Pb	Zn	Ag	Ni
Park & Fray (2009)	ICP-AES	5	5	16	3	2	1	0.1	1
Moraes (2011)	ICP-OES	12.49	0.26	35.5	3.39	1.87	5.92	0.21	3.41
Oliveira et al. (2010)	AAS	0.08	2.6	28	NA	NA	NA	NA	0.26
Yamane et al. (2011)	ICP-OES	10.57	0.26	34.49	3.39	1.87	5.92	0.21	2.63
Bizzo et al. (2014)	NM	3.08	NA	14.2	4.79	2.5	0.18	NA	0.41
Holgersson el al. (2018)	ICP-OES	0.88	1.78	39.5	3.22	0.026	0.67	0.28	1.54
Present study	ICP-MS	0.23	0.52	22.4	1.04	0.11	0.09	0.08	0.48

NA: Not analyzed
NM: Not mencioned

The quantitative analysis was carried out to obtain the concentration of elements based on grain size fraction. Copper was the main element in PCBs (22.4%), followed by Sn, Al, and Ni (1.04%, 0.52%, and 0.48%, respectively), underscoring the predominance of the element, in agreement with the XRF results. As expected, Sn came second in concentration in PCBs, possibly due to its use in soldering. Smaller amounts of other elements (Fe, Al, Zn, and Ag) were also detected. The amount of Pb observed in the present study was remarkably lower than the values observed for conventional cell phones in other works, underscoring the evolution of mobile devices. Holgersson et al. (2018) analyzed smartphones and also observed low concentrations of Pb, by comparison with conventional phones. The low amounts of Pb may be associated with the enforcement of stricter regulations that have controlled the use of the element in the manufacture of electronics since the year 2002.

The results of concentrations on grain size basis indicated that Sn, Cu, and Al accumulate more in less fine grain size ranges, as in F_4 (predominantly) and F_3, as shown in Table 2.

Table 2. Chemical composition obtained by inductively coupled plasma mass spectrometry based on grain size range

Fraction	Fe	Al	Cu	Sn	Pb	Zn	Ag	Ni
F_1 < 0.25 mm	0.02	0.08	2.66	0.1	0.02	0	0.02	0.06
0.25 mm < F_2 < 0.50 mm	0.01	0.04	2.9	0.2	0.02	0.02	0.01	0.07
0.5 mm < F_3 < 1.0 mm	0.04	0.03	4.98	0.1	0.02	0.03	0.02	0.07
1 mm < F_4 < 2 mm	0.09	0.35	7.12	0.6	0.05	0.03	0.03	0.23
F_5 > 2 mm	0.07	0.02	4.69	0	0	0	0	0.05

The highest concentrations of all quantified elements were observed in F_4 (grain size between 1 mm and 2 mm). Some of these elements, especially Cu, Fe, Al, and Ag have high commercial value. In addition, this size fraction accounted for 48% of milled PCBs, indicating that low complexity processing stages such as removal of PCBs from smartphones, detachment of components of PCBs, milling of PCBs, and sieving grain size between 1 mm and 2 mm are enough to obtain the highest possible levels of valuable metals from PCBs. In other words, these stages, which are essentially mechanical in character, are essential in the effort to recover commercially interesting metals in a WEEE recycling plant. It should be emphasized that the components of PCBs, which present the highest levels of metals, were removed from the fiberglass substrate, and that the analysis of this substrate, as shown in the present study, indicates the presence of significant amounts of metals.

Oliveira et al. (2010) observed that metals like Cu, Sn, Pb, and Zn are present mostly in intermediately sized fractions (0.3 to 1.5 mm) and less in finer fractions, where organic resins prevail. The authors also reported that though Cu may account for more than 40% of the metals present in intermediate fractions. In the present study, milling PCBs of smartphones afforded to obtain 54% of Cu in F_3 (0.5 mm – 1.0 mm) and F_4 (1.0 mm – 2.0 mm), indicating that high amounts of the metal are also obtained in intermediate grain sizes, and that the smallest amounts of metals are present in finer grain fractions (under 0.5 mm).

The results obtained agree with the XRF findings, which detected metals like Cu, Sn, Pb, and Fe.

It should be emphasized that the results obtained by other authors, as shown in Table 1, varied considerably, possibly due to origin of devices, year of production, and quantification techniques used in those studies. Moreover, since in the present study the components were removed before milling of PCBs, metals like Fe, Pb, and Ag occur mostly in components, not in substrates, where Cu and Sn prevailed. This underscores the fact that sorting components from substrates is important to prevent contamination of noble metals in components with materials present in the substrate, like polymers, epoxy resins, Cu, Sn, and other elements identified at small amounts.

It is also important to note that, due to the lack of homogeneity even after milling, grain size separation, and sample size reduction, the chemical characterization of PCBs is a difficult task. Considering that the ICP-MS analysis used only 1 g of sample, like the other assays carried out in this study, the difference in values observed not only in the present work, but also by other authors, could be clarified based on this characteristic of the material.

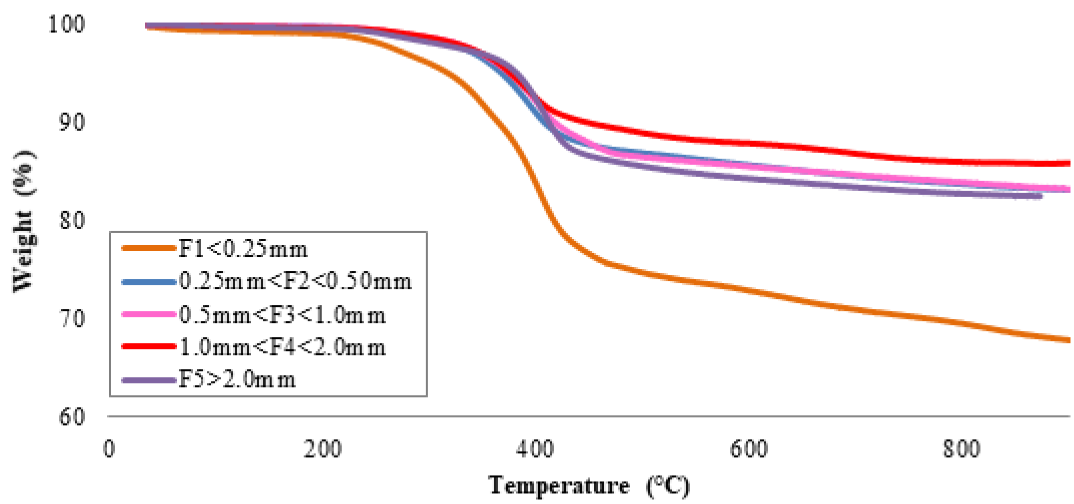
Compared with XRF, the use of ICP-MS was essential in the present study, since it was possible to analyze elemental composition quantitatively. However, it should be emphasized that the technique requires the careful preparation of samples, which is time consuming and increases costs due to the need to use reactants and glassware of high purity.

4.8 Thermogravimetric analysis

Knowing that the polymeric materials are also present in the composition of PCBs, TGA was conducted to identify the thermal behavior of this material in the five fractions analyzed.

The curves representing weight in function of temperature overlapped, as shown in Fig. 4, revealing a rather similar behavior between fractions.

Figure 4. Thermogravimetric analysis of fractions of printed circuit boards



The highest weight was recorded for F_1 (32.12%), followed by F_5 (17.5%). Both fractions contained the highest amount of polymers in the aqua regia leaching test and had the lowest density, confirming the results of both assays. Residual material was observed in all fractions: while the lowest value was recorded for F_1 (67.78%), the highest was observed for F_4 (85.81%), indicating the presence of a large amount of filler that could include metal or even composite material in F_4.
The loss of weight was almost imperceptible in the range of 30ºC to 250ºC. Carevarolo Jr (2013) reported that humidity is released when environment temperature nears 100ºC. Higher loss of weight occurred in the 250ºC to 500ºC range, possibly due to the degradation of polymers, epoxy resins, and phenols that are used as curing agents.

5. CONCLUSION

The results of the present study allow concluding that:
The cell phones collected were produced by six manufacturers and were of several different models, which explains why the study material was rather heterogeneous, as observed with consumption and disposal patterns.
The highest concentration of Cu, Al, Fe, Ag, and Ni in PCBs of smartphones is present in the grain size fraction 1 mm - 2 mm. As this fraction of PCB concentrates the highest amount of metals, it may be used on industrial scale to obtain most PCB metals, like the metals cited. This is possible after disassembly of smartphones to remove PCBs, milling, and sieving the 1 mm to 2 mm grain size fraction.
Grain size distribution and sorting of the five fractions studied indicated that 48% of the mass of PCBs after milling remains between at between 1 mm and 2 mm (F4), and that this fraction presented the highest amount of metals, which affords to conclude that it would be the best fraction to be used in the recycling of Fe, Al, Cu, Sn, Pb, Zn, Ag, and Ni on industrial scale, which were quantified in this study. Additionally, this fraction enables the concentration of these metals, reducing milling time and energy significantly.
Smartphones are composed of approximately 17% of PCBs by weight, and the substrates of the PCBs (printed circuit boards without electronic components) used in the devices analyzed are

formed basically by fiberglass and epoxy resin, in addition to metals that were quantified in this study – Cu (22.4%), Sn (1.04%), Al (0.52%) and Ni (0.48%). The characterization of PCBs based on the mechanical removal of components soldered to PCBs indicated the presence of Cu, low amounts of Pb, Sn and other elements, which remained from the devices removed. Therefore, the segregation of PCBs from devices, which presents the elements of high added value, is beneficial, since it reduces the contamination of these metals with polymer and fiberglass, if these are processed together. In this sense, the main contribution of this study was to reveal that the highest levels of metals in smartphone PCBs were observed in the grain size fraction between 1 mm and 2 mm, and that the fiberglass composite material has considerable amounts of economically valuable metals. The mechanical processing after removal of soldered components was efficient to obtain metals, especially Cu (22.4%), in the grain size fraction between 0.25 mm and 2 mm. However, the method was not efficient to obtain noble metals like Au and Ag, due to the small amounts thereof. Although these metals were detected at trace levels in components like connectors, integrated circuits, and resistors, requiring special removal techniques.
Toxic metals like Cd, Pb, and Sn were detected in the fractions of PCBs, underscoring the importance of appropriate disposal of WEEE so as to prevent not only environmental problems, but also urban and public health issues.
The low level of Pb may also be associated with stricter regulations worldwide: the European Union restricts the use of this element as directed in the RoHS incentive.

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