JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY 2021;14:2992–2997

Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

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

Original Article

Cement matrix containing lightweight aggregate based on Non-Metallic Fraction Printed Circuit Boards (NMFPCB'S)

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ARTICLE INFO

Article history:
Received 26 April 2021
Accepted 23 August 2021
Available online 27 August 2021

Keywords:
Recycling
Waste electrical and electronic equipment (WEEE)
Printed circuit boards
Lightweitght aggregates
Axial compression strength

ABSTRACT

Materials such as river sand, used in construction, have a high demand, and thus generate great environmental impacts while being extracted, such as erosion of the rivers banks and your siltation. With the increasing restriction of river sand extraction which can generate a reduction in the product's offer in the civil construction sector, it is necessary to develop waste recycling technologies for the production of sands with less environmental impact. One of the alternatives for the production of mortar for construction is the replacement of sands extracted from rivers by waste from other industries, such as the electronics industry that presents large and growing production worldwide, due to technological advances. Thus, this work aims to evaluate the influence of partial replacement of quartz sand by lightweight aggregate based non-metallic fraction of printed circuit boards (NMFPCB's) on the properties of cementitious matrix in the fresh and hardened states. For this, the electronic components of the printed circuit boards (PCBs) were removed, they were grinded and then through magnetic and electrostatic separation processes to separate the most valuable and abundant part of metals. The water to cement ratio was 0.48 in all the experiments, the Portland cement to sand ratio was 1:3 (in mass) for the control, and the mortars with NMFPCB's replacement of sand by volume of 25% and 50% were also made. These were characterized mechanically by axial compressive strength test at different ages. The partial results showed that with the increase of sand substitution by NMFPCB's there was a reduction of the mortar consistency index in the fresh state. Results showed that matrix that suffered the substitution of sand by light aggregate, decreased the compressive strength in relation to the reference, but have potential to use in construction industry as blocks or non-structural elements.

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https://doi.org/10.1016/j.jmrt.2021.08.090

1. Introduction

The environmental issues surrounding waste management have been the source of frequent studies and research, as well as concerns that they directly affect the quality of life of society. Electronic waste, the result of the great development of the electronic industry in its multiplicity of applications, the massive marketing actions of manufacturers and retailers, and the consumption habits of modern society, represent the fraction of municipal solid waste that has been presenting the largest annual growth in most countries the world [1]. Parallel to this growth, is the concern to give an environmentally correct destination to this material that, due to the characteristics of its constituent elements, may present a high degree of toxicity [2]. Electronic waste has been called "urban ore" because of the high concentration of metals in its composition and because it is within the city environment. Its recycling allows the recovery of a wide range of elements, which generally happens with greater energy efficiency when compared with the processes employed in obtaining these same elements when present in ores [3]. From the economic and financial point of view, many of the recycling operations are also very advantageous when properly operationalized [4]. Brazil implemented the National Solid Waste Policy in August 2010, through Law No. 12,305 [5]. Where the shared responsibility of the entire manufacturing-trading chain has been established, with the obligation to set up the necessary reverse logistics structure that allows the collection of discarded material by users and their forwarding to the redistribution centers for reuse or recycling plants.

Given this scenario, this paper analyzes the feasibility of an alternative and temporary solution for the disposal of the most environmentally critical part of electronic waste, which is printed circuit boards, proposing that they be crushed and ground and that material resulting from this process is diluted in the composition of cementitious matrix applied in the construction industry. Several studies have analyzed the incorporation of different materials into concrete or concrete blocks. Materials such as sand and gravel, used in construction, have a high demand, and thus generate great environmental impacts as they are extracted, such as erosion of banks and river beds, in the case of sand. An example cited by Volpato [6] is the sand used in the metropolitan region of Porto Alegre, Brazil, from the extraction of the Jacuí River. This disorderly and sometimes illegal extraction has caused erosion of the rivers banks and your siltation.

Thus, an alternative is the partial replacement of sand by new materials. With the increasing prohibition of river sand extraction and the scarcity of natural sands, it is essential that the construction sector seeks to adopt an environmental and sustainable stance through technological developments of waste recycling processes [7]. One of the alternatives for civil construction, focusing on the environmental and economic points, in relation to the sand supply, is the substitution of natural sand (extracted from the rivers) by waste, for the production of mortars. Construction is one of the sectors that generates the most construction and demolition waste (CDW), and it is the sector that consumes the most non-renewable natural resources.

Currently, in 2019, there is a large and growing production of electro-electronic products worldwide, an order of 9% per year. Countries such as China and Taiwan are responsible for producing over 200 million square meters of PCBs per year for electronic devices and often disposing of these devices incorrectly [8]. As they contain heavy metals and toxic substances in their composition, they increase the potential to cause environmental impact related to their incorrect destination. Processing PCBs to recover valuable metals uses a combination of physical-mechanical and chemical processes and the recycling of different fractions of materials from the e-waste depends on the correct separation during disassembly as well as on the control of processing [9]. Recycling processes aimed at recovering metals from PCBs have aroused great interest recently, but, there is a fraction of this waste that is not utilized and has uncertain destination, e.g. the non-metallic fraction and the dust generated during metal recovery processes [10]. The use of waste in construction has shown important environmental benefits, with respect to the reduction of extraction, mining and disposal, as well as the generation of new mortars and concrete. Taking this scenario into account, the present work analyzes the technical feasibility of an alternative solution for the disposal of a part of the electronic waste, in environmental terms, which are the printed circuit boards, proposing that they are crushed and ground and that the resulting material can be used in the study as a lightweight aggregate in cementitious matrix. Therefore, the objective of this work was to evaluate the partial replacement of sand by Lightweight Aggregate (LA) Based on Non-Metallic Fraction Printed Circuit Boards (NMFPCB'S) in the mechanical and environmental properties of mortars.

2. Experimental

The Portland High Strength Initial Cement (CP V ARI) binder was used. This cement was chosen because it has a low amount of mineral additions, according to NBR 5733 [11]. According to the manufacturer, the compressive strength at 7 days is greater than 34 MPa, as specified by that standard. From the particle size composition of Lightweight Aggregate (LA) Based on Non-Metallic Fraction Printed Circuit Boards (NMFPCB'S), fineness modulus is 3.70, as shown by the particle size distribution in Table 1.

The natural aggregate was prepared to maintain the same particle size composition between the aggregates. The determination of the specific mass of LA was performed by adapting to the NBR NM 52 standard [12]. The specific gravity value

Table 1 – Particle size distribution of the Lightweight Aggregate.

Mesh sieve (mm)	% retained	% accumulated
1.2	80	80
0.6	15	95
0.3	2	97
0.15	1	98
<0.15	1	100

found was 1.70 g/cm^3. The natural aggregate used was quartz sand from Jacuí River (RS). The specific gravity of the sand was determined by the procedures prescribed by NBR NM 52 standard [12], and the value obtained was 2.61 g/cm^3.

Waste printed circuit board (PCBs) was donated by a waste recycling company from Novo Hamburgo/RS. In this company, there were numerous models of plates that were made available for use. The plates were chosen as samples according to the criterion of obtaining the largest number of plates of the same model and with the smallest possible number of components, in order to avoid many metallic parts next to the samples, which could damage the equipment, until reaching a 17.8 kg sample. Figure 1 shows the PCB waste processing flowchart. To chemically characterize the composition of the NMFPCB's used in the present study, X-Ray Fluorescence analysis was performed, where the elements found were listed in Table 2. The PCBs have their fiberglass composition impregnated in epoxy resin which in turn is composed of hydrocarbons. Fiberglass is composed of oxides such as SiO_2, CaO, Al_2O_3 and MgO, justifying its detection in the analysis. The copper found is due to losses in the separation process. On the other hand, aluminum, although part of it may come from a capacitor casing and thus also be due to losses in the separation process, has another source such as fiberglass itself in the form of alumina. The other elements present in smaller amounts come from other components as well as its additives. In addition, the equipment used, Energy dispersion X-ray fluorescence (FRX) was a multi-element analytical technique capable of identifying elements with atomic number Z greater than or equal to 12. Thus, the balance (51,27 wt%) is assigned to elements with atomic number Z less than 12, as C, H and O.

Reference matrix (0% LA) and two other matrix containing 25%, 50% LA substitution to the sand river were prepared. The water to cement ratio (w/c) was 0.48 in all the experiments, the Portland cement to sand ratio is 1:3 (in mass) for the control, and the mortars with NMFPCB's replacement of sand by volume of 25% and 50% were also made. The ratios 1:3 (cement:sand) and 0.48 (w/c) were adopted based on NBR 7215 [14].

Table 2 – Elemental composition FRX analysis of the Non-Metallic Fraction Printed Circuit Boards (NMFPCB'S) (% of mass).

Si	Ca	Cu	Al	Mg	S	Bi	Sn
14.05	12.63	9.82	7.59	1.40	0.50	0.46	0.39
Fe	Ba	Rb	Th	Ti	Ni	Au	Pb
0.38	0.32	0.27	0.18	0.17	0.13	0.12	0.10
Cl	Zn	Sr	K	Mn	Cr	Ag	Bal
0.10	0.10	0.07	0.05	0.04	0.02	0.01	51.28

As the specific gravities of LA and sand are distinct, the replacement was performed by compensating the density. For this, the cementitious matrix containing 0%, 25%, 50% LA were prepared. Table 3 shows the quantities used for the preparation of the reference cementitious matrix - 0% LA - and the matrix with the substitution of sand for LA, in the proportions of 25% and 50%, where the substitution was proportional to the sand particle size distribution used in this work.

The use of molds with different dimensions than that established by NBR 7215 [14] was due to the fact that the quantities of LA produced were not sufficient for the preparation of larger specimens. Twelve specimens were molded with each percentage of LA and the reference, providing tests at ages 7, 28, and 91, totaling 36 samples (with diameters of 3 cm and heights of 6 cm) for the compressive strength test. Figure 2 illustrates the samples of cementitious matrix containing different levels of LA, after being removed from plastic molds.

The PC's were unmolded after 24 h in the humid chamber, with 22 °C and 95% humidity. Samples were taken from wet

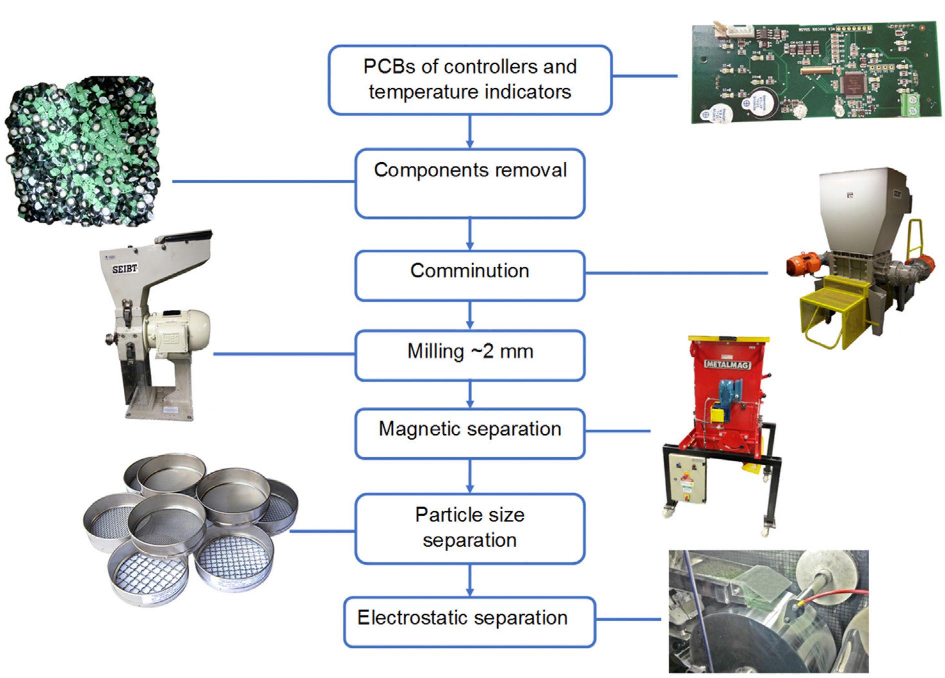

Fig. 1 – Flowchart of the processing steps. Adapted from Schneider, E.L. et al. [13].

Table 3 – Quantity of materials used for the preparation of cementitious matrix.

Cementitious Matrix (LA%)	Cement (g)	Sand		Lightweight Aggreg. (LA)		Water (g)	water/cement ratio
		Mesh sieve (mm)	Amount (g)	Mesh sieve (mm)	Amount (g)		
0	335	1.2	804	1.2	0	160.8	0.48
		0.6	150.75	0.6	0		
		0.3	20.1	0.3	0		
		0.15	10.05	0.15	0		
		<0,15	20.1	<0,15	0		
25	335	1.2	603	1.2	129.43	160.8	0.48
		0.6	113.06	0.6	24.27		
		0.3	15.08	0.3	3.24		
		0.15	7.54	0.15	1.62		
		<0,15	15.08	<0,15	3.24		
50	335	1.2	402	1.2	258.86	160.8	0.48
		0.6	75.38	0.6	48.54		
		0.3	10.05	0.3	6.47		
		0.15	5.03	0.15	3.24		
		<0,15	10.05	<0,15	6.47		

cure to the ages determined for mechanical testing. The samples were subjected to mechanical characterization (axial compressive strength tests). To determine the axial compressive strength, an universal electromechanical and micro processed testing machine EMIC model DL 20000, which has a maximum load capacity of 200 kN, was used. The samples were submitted to compressive strength tests at 7, 28 and 91 days. For each age four samples were tested.

An environmental characterization of the cement matrices was carried out through leaching tests (NBR 10005, ABNT 2004) and solubilization (NBR 10006, ABNT 2004). The samples submitted to compressive strength tests at the age of 91 days were comminuted and the material passing through the 9.5 mm sieve was submitted to environmental tests.

3. Results and discussion

Table 4 shows the mean values and standard deviations of compressive strength of the reference cementitious (M0 - 0%) and LA 25% (M25) and 50% (M50) matrix at the ages of 7, 28 and 91 days. The mean value obtained for the compressive strength of the reference value at 7 days was 17.67 MPa (Table 4), lower than the expected limit for testing with Portland Cement CP V ARI, which according to the manufacturer is higher than the NBR 16697 standard [15], which is 34 MPa for the w/c ratio 0.48, described in NBR 7215 [14] for compression test. It is important to note that the particle size composition for the Portland cement compressive strength test uses 4 grit sizes of standard sand. In the present study, as a function of LA granulometry, 5 granulometries were used, so this change may influence the results when comparing with NBR 7215 [14], as well as the specimen sizes.

However, it is important to emphasize that the cementitious matrix studied in the present work presented cement consumption around 510 kg/m^3, considered a high consumption in civil construction, and consequently of higher economic value. This is at related the reference mortars (0% LA) prepared at 1:3 (cement:sand) ratio. As the matrix containing 50% LA reached the compressive strength of 11.13 MPa, it is understood that there is a possibility of proportion optimization and consequently cost reduction. As the objective of the present work was to evaluate only the influence of LA on the properties of cementitious matrix, the trace optimization and the economic study could be studied in future works.

One factor to be considered in the analysis of the compressive strength reductions is the possible influence of the physical characteristics of the LA on the degree of mortar densification, which occurs in the cement mortar manufacturing stage, due to the lower specific gravity of the light aggregate (1.70 g/cm^3) in relation to the specific gravity of the sand (2.61 g/cm^3). The occurrence of reduced compressive strength with the presence of LA was also verified by Wang and Meyer [16], who related this fact mainly to the interface with lower adhesion between LA

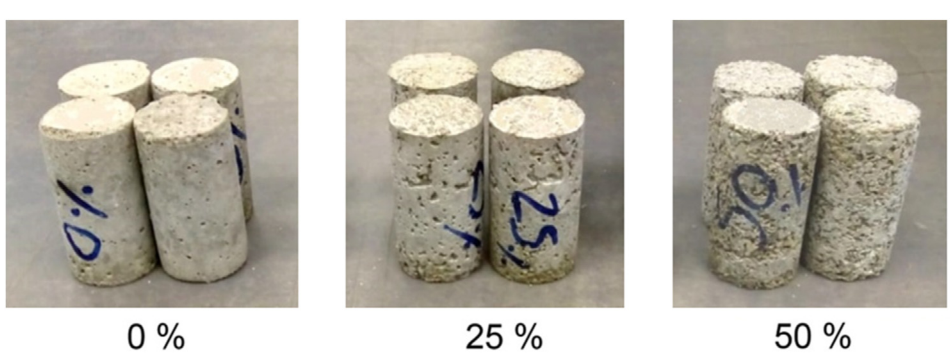

Fig. 2 – Specimens of mortars containing different levels of LA: 0%, 25% and 50%.

Table 4 – Average compressive strength, standard deviation and coefficient of variation of cementitious matrix containing different Light Aggregate (LA) contents, at ages 7, 28 and 91 days (MPa).

Content of LA	Age (days)	Average compressive strength (MPa)	SD (MPa)	CV (%)
M0	7	17.67	1.00	5.68
M0	28	13.68	2.38	17.39
M0	91	24.17	2.04	8.43
M25	7	15.98	1.33	8.32
M25	28	15.63	0.07	0.45
M25	91	17.17	1.47	8.57
M50	7	11.13	0.14	1.26
M50	28	13.61	0.21	1.52
M50	91	14.06	0.54	3.81

SD – Standard Deviation.
CV - Coefficient of variation.

and the cementitious mass, in relation to the original state of the mortars, provided by the increase in substitution levels of natural aggregates.

Another factor, possible contributor to the reduction of compressive strength, would be the constitution of part of the light fraction components of crushed electronic waste. According to Naia [17] this fraction is composed of filament-shaped PCB substrate glass fiber and aluminum oxide-coated micro-films. Both fiberglass filaments and films are fully flexible, being an undesirable feature for cementitious matrix where mechanical rigidity is sought. The other PCB fragments have smooth surfaces, making it difficult for the binder to adhere to these fragments in the solidification process, which should probably contribute to a localized reduction of mechanical strength.

The leaching and solubilization results are shown in Tables 4 and 5 respectively. Analyzing the results of the leached extracts of the Matrix with 25% and 50% of LA, and considering the concentrations of cadmium, lead, copper and mercury, the cement matrices are classified as non-hazardous (class II) according to the maximum concentration allowed in leaching tests of NBR 10004:2004 [18] Annex F. In relation to solubilization tests, considering the concentrations of these elements, the LA is classified as Class II–B Inert, according to the maximum concentration allowed in leaching tests of NBR 10004:2004 [18] Annex G. The leaching and solubilization results indicate that although the copper contained in the PCI's has not been completely removed after the separation steps to obtain the LA, this does not compromise the use in cement matrix applications proposed in this work (see Table 6).

Table 5 – Results of the leached extracts of cement matrices containing distinct contents of LA (%), at age 91 days.

Sample	Cadmium (mg/L)	Plumb (mg/L)	Copper (mg/L)	Mercury (mg/L)
Matrix with 25% of LA	0.014	0.212	18.236	0.03
Matrix with 50% of LA	0.143	0.216	11.694	<D.L
maximum amount allowed by NBR 10004:2004	0.5	1.0	not specified	0.1
D.L.	0.001	0.032	0.004	0.007

<D.L = contents lower than the Detection Limit of the equipment.

Table 6 – Results of the solubilized extracts of cement matrices containing distinct contents of LA (%), at age 91 days.

Sample	Cadmium (mg/L)	Plumb (mg/L)	Copper (mg/L)	Mercury (mg/L)
Matrix with 25% of LA	<D.L	<D.L	0.082	<D.L
Matrix with 50% of LA	<D.L	<D.L	0.225	<D.L
maximum amount allowed by NBR 10004:2004	0.005	0.01	2.0	0.001
D.L.	0.001	0.032	0.004	0.007

<D.L = contents lower than the Detection Limit of the equipment.

4. Conclusion

With the increase of sand substitution by Lightweight Aggregate (LA) based on Non-Metallic Fraction Printed Circuit Boards (NMFPCB'S) there was a reduction of the mortar consistency index in the fresh state. Moreover, the substitution of sand by LA decreased the compressive strength in relation to the reference mortar. Although a reduction in compressive strength was observed with increased sand substitution by NMFPCB, the LA has potential as partial replacement of sand for the manufacture of concrete blocks without structural function or other components without structural function in civil construction industry. In environmental tests (leaching and solubilization) of matrices containing LA up to 50%, concentrations of Cd, Pb, Cu and Hg were not verified above the maximum limit allowed by NBR 10.004 [18]. Therefore, cementitious matrices containing up to 50% of LA were classified as Class II – Inert.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors are grateful to Reverse – Gerenciamento de Resíduos Tecnológicos, Novo Hamburgo – RS – Brasil by donating the PCBs used in this study and to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES/PROEX 23038.000341/2019–71 0491/2019) for financial support.

REFERENCES

[1] Oliveira CR, Bernardes AM, Gerbase AE. Collection and recycling of electronic scrap: a worldwide overview and

comparison with the Brazilian situation. Waste Manag 2012;32:1592–610.
[2] Gerbase AE, Oliveira CR. Reciclagem do lixo de informática: uma oportunidade para a química. Quím Nova 2012;XY:1–7. abr.
[3] Parson D. Printed circuit board recycling in Australia. In: 5th Australian conference on life cycle assessment; 2006. Melbourne, nov.
[4] Portugal SM, Dantés GB. Diagnóstico da geração de resíduos de equipamentos elétricos e eletrônicos (REEE). 2010. Revista Resíduos em Referência 2010;1:16–21. dez.
[5] Brasil. Lei N° 12.305, de 02 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos; altera a Lei N° 9.605 de 12 de fevereiro de 1998; e dá outras providências. Diário Oficial da União, Brasília, DF, 03 de agosto de 2010.
[6] Volpatto F. Argamassas Utilizando Agregado Leve à Base de Resíduo de Carvão Vegetal (RCV). 2013. In: Dissertação (Mestrado Profissional em Tecnologia de Materiais e Processos Industriais). Universidade Feevale; 2013.
[7] Heineck S. Desempenho de Argamassas de Revestimento com Incorporação da Fração Miúda da Britagem de Concreto. In: Dissertação apresentada ao Programa de Pós-Graduação em Engenharia Civil da Universidade do Vale do Rio dos Sinos – UNISINOS; 2012. São Leopoldo, Fevereiro de.
[8] Filho JH, Gobbi A, Pereira E, Tanaka RS, Medeiros MH. Atividade pozolânica de adições minerais para cimento Portland (Parte II): Índice de atividade pozolânica com cimento Portland (IAP), difração de raios-X (DRX) e termogravimetria (TG/DtG). Materia 2017;22(3). Rio de Janeiro.
[9] Adam AP, Gonçalves JVRV, Robinson LC, da Rosa LC, Schneider EL. Recycling and mechanical characterization of Poly¬mer blends present in printers. Mater Res 2017;20(suppl. 2):202–8.
[10] Schneider EL, Grassi GD, Amico SC, Chaves RA, Mazzuca DC, Robinson LC. Reaproveitamento de resíduo de placas de circuito impresso como cargas em compósitos de polipropileno. Rev Mater 2020;25(3):1–11.
[11] Associação Brasileira de Normas Técnicas. NBR 5733: cimento Portland com alta resistencia inicial. 1991. p. 5. Rio de Janeiro.
[12] Associação Brasileira de Normas Técnicas. NBR NM 52: agregado miúdo - determinação da massa específica e massa específica aparente Agregado miúdo - determinação da massa específica e massa específica aparente. 2009. p. 5. Rio de Janeiro.
[13] Schneider EL, Hamerski F, Veit HM, Krummenauer A, Cenci MP, Chaves RA, et al. Evaluation of mass loss in different stages of printed circuit boards recycling employed in temperature controllers. Mater Res 2019;22(1).
[14] Associação Brasileira de Normas Técnicas. NBR 7215: resistência à compressão do Cimento Portland. 1996. p. 8. Rio de Janeiro.
[15] Associação Brasileira de Normas Técnicas. NBR 16697: cimento Portland – requisitos. 2018. p. 9. Rio de Janeiro.
[16] Wang R, Meyer C. Performance of cement mortar made with recycled high impact polyestyrene. Cement Concr Compos 2012;34:975–81.
[17] Naia GL. Desenvolvimento de produto sustentável: aproveitamento de placas de circuito impresso descartadas como agregado na fabricação de blocos de alvenaria para construção civil. 140 f. Dissertação (Mestrado em Engenharia de Materiais) – departamento de Engenharia de Materiais. Itajubá: Universidade Federal de Itajubá; 2014.
[18] Associação Brasileira de Normas Técnicas. NBR 10004: resíduos sólidos – classificação. 2004. p. 71. Rio de Janeiro.