

# Reuse of printed circuit boards substrate in the production of mortars

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## Abstract

Recycling electronic waste is one of the main environmental challenges faced by society today. In this sense, the purpose of this study is to evaluate the effect of using the residue of printed circuit boards (PCB) as a substitute for sand in mortars. The boards were taken from discarded electronic equipment and, to obtain the granular material, the boards, free of their components, were crushed. The residue obtained was sieved and separated into four granulometric ranges: # 1.2 mm; # 0.6 mm; # 0.3 mm and # 0.15 mm. Mortars were produced with partial replacement of 5% and 10% of the sand with the equivalent volume of residue in each of the size ranges, in addition to a reference mortar, without residue. For the characterization of the mortars, compressive strength, water absorption, percentage of voids and density tests were performed, in addition to analysis by scanning electron microscopy and environmental, leaching and solubilization, analyses. In general, the properties of the mortars, with the incorporation of the PCB residue, were not affected by the introduction of the residue, making its use feasible. However, as it is classified as non-inert in environmental analysis it is necessary to control its final disposal.

**Keywords:** Electronic waste; Printed Circuit Board (PCB); Mortar; Recycling.

## Reaproveitamento do substrato de placas de circuito impresso na produção de argamassas

## Resumo

A reciclagem do lixo eletrônico é um dos principais desafios ambientais enfrentados pela sociedade atualmente. Encontrar novas possibilidades de uso para esses resíduos pode auxiliar a solucionar alguns problemas. Neste sentido, a proposta deste trabalho é avaliar o efeito do uso do resíduo de placas de circuito impresso (PCB), como substituto da areia em argamassas. As placas foram retiradas de equipamentos eletrônicos descartados e, para a obtenção do material granular, as placas, livres de seus componentes, foram trituradas. O resíduo obtido foi peneirado e separado em quatro faixas granulométricas: # 1.2 mm; # 0.6 mm; # 0.3 mm e # 0.15 mm. Foram produzidas argamassas com substituição parcial de 5% e 10% da areia pelo volume equivalente do resíduo de cada uma das faixas granulométricas, além de uma argamassa de referência. Para a caracterização das argamassas foram realizados ensaios de resistência à compressão, absorção de água, índice de vazios e densidade, além de análise por microscopia eletrônica de varredura e análises ambientais, de lixiviação e solubilização. As propriedades das argamassas com o resíduo de placa de circuito impresso não foram afetadas pela introdução do resíduo, viabilizando a utilização do mesmo. No entanto, por ser classificado como não inerte nas análises ambientais, segundo a norma NBR 10004:2004, é necessário controle na sua disposição final.

**Palavras-chave:** Lixo eletrônico; Placas de Circuito Impresso; Argamassa; Reciclagem.

## 1 Introduction

The growing consumption of electronic equipment in the world is notorious. Consumerism of modern society and the fact that equipment is quickly becoming obsolete

makes this industry grow at an accelerated rate. As a result, the volume of waste generated, called electronic waste or e-waste, grows. According to the UN's Global E-waste

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Monitor 2020 [1], world e-waste production in 2019 was 53.6 million tons, up 21% in just five years. Of this total, only 17.4% was collected and recycled.

Among the various pieces of equipment present in electronic waste, we can highlight laptop and desktop computers, printers, stabilizers, tablets, smartphones, televisions and older computer monitors, known as CRT (cathode ray tube), which contain toxic substances such as cadmium, mercury and lead. Many of these devices have valuable metals in their composition, such as gold, silver, copper and platinum. The correct use of this material, with the recovery of noble metals, could generate a profit of \$57 billion in 2019 alone, an amount greater than the gross domestic product of most countries [1].

According to Ongondo et al. [2], the materials present in electronic waste are diverse. Ferrous metals, due to their density, account for more than half of the total weight of electronic waste (60%), followed by polymers (21%) and non-ferrous metals, including precious metals, with (13%) of the total; other materials account for the rest of the weight.

Finding new uses for electronic waste can help to solve some problems related to disposal. Research studies related to electronic waste address various topics such as: waste management [3,4], new techniques and procedures for recycling [5,6], and characterization and recovery of precious metals, such as gold and copper [7-9]. It is worth mentioning that informal recycling practices of these residues to recover precious metals are common in Asian and African countries, with damage to the environment and the health of workers [10,11]. Another recurring topic is the recovery, characterization and recycling of the polymeric parts of the waste, which accounts for a significant part of the volume generated. Part of these polymers are thermoplastic and can be recycled through conventional extrusion and injection techniques [6,12-14].

A major part of electronic waste that is difficult to recycle is the printed circuit boards (PCBs). These are part of almost anything that may involve technology and, in general, are not apparent, but lie within the equipment/appliances to which they belong. The boards house several electronic components and are responsible for the equipment's functionalities. They are formed by layers of fiberglass impregnated with a thermoset polymer, usually epoxy or polyester, and by thin films of metallic substances. Since PCBs are manufactured in various types and sizes any "average" of the constituent materials must be approached with caution [15]. Medeiros [16], determined the percentages of metals, polymers and ceramics in obsolete computer PCBs, obtaining the following result: 46% of metals, 23.3% of polymers and 30.6% of ceramic material. The intimate mixture between these materials makes it difficult to recycle PCBs [15,16]. It is worth emphasizing that the polymer used in these plates is generally of the thermoset type (epoxy, phenolic or polyester), which cannot be recycled by melting, as well as the thermoplastics present in the equipment cases.

Seeking alternatives for recycling PCBs, this study evaluated its use as a substitute for aggregates in mortars for civil construction. Mortars are present in various stages of a construction work and are used for different purposes: joining blocks or bricks; coating walls, ceilings and floors; laying tiles and leveling surfaces. For its production, several natural resources are used, whose disorderly exploitation can negatively impact the reserves of these raw materials, especially when close to urban centers where consumption and demand are very high. Like concrete, mortars have a high potential to incorporate different types of granular waste, mainly in partial or total replacement of the fine aggregate. When incorporating a residue into the mortar, its functionality must be guaranteed, which is evaluated through properties, both in the fresh and hardened state, specified in standards such as, for example, consistency, compressive strength, water absorption, percentage of voids and density.

Research regarding the incorporation of residues in mortars is always relevant because, in some cases, the mixture has the capacity to encapsulate toxic wastes. In general, civil construction materials are inert, do not decompose and do not change their composition over time and can, therefore, be disposed of in sanitary landfills and even recycled. In the case of using of residues in mortar, it is also necessary to evaluate the potential for leaching and solubilization of this residue, to ensure that substances that harm the environment are not released, either during the use of the material or after its disposal. Therefore, when incorporating a waste into construction materials, even if the final product meets the technical specifications, it is necessary to check whether its environmental classification meets the requirements for inert material. In Brazil, these requirements are defined by the NBR 10004:2004 standard [17].

There is a paucity of studies in the literature that comprehends the reuse or recycling of PCBs in mortar and concrete. Alagusankareswari et al. [18] evaluated the use of PCB ground residue in concrete and obtained a product with a slightly lower compressive and tensile strength than the reference sample. Premur et al. [19] also used the granular residue of PCBs as a partial substitute for sand in concrete and obtained lower compressive strength results than the reference sample. In the study by Gomathi Nagajothi and Felixkala [20], however, the plates were used in the form of strips, as a reinforcing element for the concrete. The results showed a 10% gain in the compressive strength of concrete, in relation to the reference mixture. Huang et al. [21] studied the use of resin powder and recycled PCB fiberglass as a substitute for sand in concrete. They obtained results close to those of the reference concrete using percentages of at most 10% resin powder and 2% fiberglass.

This study aims to evaluate the use of the residue obtained from the crushing of PCBs to partially replace sand in the production of mortars. The influence of particle size and percentage of residue used will be evaluated. It is intended to find new possibilities of use for disposed PCBs in order to reduce the use of natural resources.

## 2 Materials and methods

### 2.1 Materials

The PCBs used in this study were obtained from local businesses in the state of Espírito Santo, Brazil. These are mainly computer boards, cordless phones, remote controls, and computer power sources. The electronic components of the boards (resistors, capacitors, diodes, expansion slots and chips) were removed with the aid of a thermal blower. The plates were cut on a guillotine, in a compatible size to be inserted and crushed in a forage mill.

After crushing, the residue obtained was sieved for 15 min in sieves with the following mesh openings: 0.15 mm, 0.3 mm, 0.6 mm, 1.2 mm and 2.4 mm. Four particle size ranges were selected: Range 1 – Retained in the 0.15 mm sieve; Range 2 – Retained in the 0.3 mm sieve; Range 3 – Retained in the 0.6 mm sieve; Range 4 – Retained in the 1.2 mm sieve.

For the production of mortar, in addition to the residue, the following inputs were used: cement, sand and water. The cement is of the Portland CPV ARI RS type, aiming at the future use of the mortar in the production of precast. The sand comes from a river bed, with a fineness modulus of 2.31 and a maximum characteristic dimension of 2.36 mm. The water was supplied by the local public supply network.

### 2.2 Methods

#### 2.2.1 Characterization of the PCB residue

The morphology of the residue, after grinding was analyzed by scanning electron microscopy. The equipment used was the ZEISS scanning electron microscope (SEM), model EVO MA10.

For the partial replacement of sand with residue in mortar manufacturing, it was necessary to know the unit weight of sand and residue, so that the same volume of material is replaced. In the case of residue, the test was performed for the four selected particle size ranges. The unit weight was determined according to the NBR NM 45 standard [22].

#### 2.2.2 Specimens preparation and tests

The mix proportion used was 1:3 (cement: sand) and water/cement ratio of 0.48, according to NBR 7215 [23]. Considering the studies by Siddiqui et al. [13], Gomathi Nagajothi and Kala [20] and Moncea et al. [24], the residue was incorporated, in partial replacement of sand, in proportions of 5% and 10%. Due to the difference between the unit weights of sand and residue, volume compensation was carried out. For each mix, a certain percentage in sand weight (5% or 10%) was removed and its volume verified. This volume was replaced with the equivalent volume of residue.

The mortar preparation procedure was carried out in accordance with the NBR 7215 standard [23]. Nine cylindrical specimens (5 cm x 10 cm) were molded for each mix. Considering the four particle size ranges of the residue and the two replacement percentages, 5% and 10%, in addition to the reference mortar, a total of nine mix were prepared.

Twenty-four hours after molding, the specimens were demolded and submerged in water saturated with lime for 28 days to cure. After curing, tests were carried out to determine water absorption, percentage of voids and density, according to NBR 9778 [25]. The compressive strength test was performed following the NBR 7215 standard [23].

After the compression test, specimens fragments were placed in acetone for 24 hours to stop the cement hydration process and put in an oven at 40°C for acetone evaporation. The fragments were investigated by scanning electron microscopy. The equipment used was the ZEISS scanning electron microscope (SEM), model EVO MA10. This analysis was performed for mortars with 10% residue, in addition to the reference mortar.

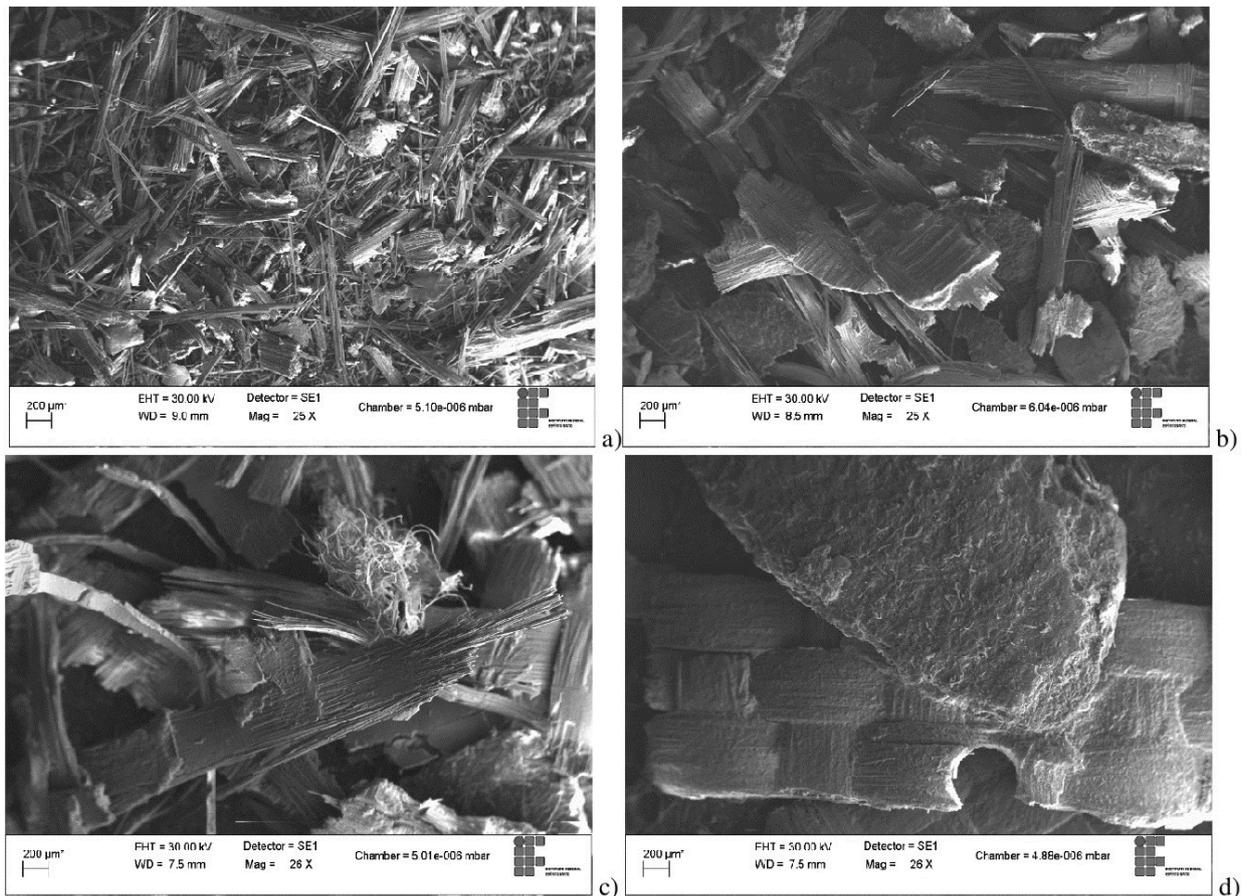
In order to verify the classification of the material, according to ABNT NBR 10004 [17], leaching and solubilization tests were performed by specialized companies. This test was carried out for the mortar with 5% residue, in two granulometric ranges: 0.6 mm and 1.2 mm. The ABNT NBR 10004 [17] standard classifies solid waste as to its potential risks to the environment and public health, so that they can be properly managed.

## 3 Results and discussion

### 3.1 Characterization of the PCB residue

Figure 1 shows morphology images of the particles of waste obtained in the SEM for the different particle size ranges. In the residue retained in the 0.15 mm sieve, the fibrillar format predominates. Large amounts of dispersed glass fibers with a short length, maximum 1 mm, can be observed, as well as grouped glass fibers in small bundles. In small amounts, non-fibrous particles are also found. As for the residue retained in the 0.3 mm sieve, particles of different shapes are observed, most of them elongated and glass fibers agglomerated by resin in the form of larger diameter bundles.

The residue retained in the 0.6 mm sieve is similar in shape to that retained in the 0.3 mm sieve, but with larger dimensions. The coarser residue, retained in the 1.2 mm sieve, has particles of rectangular or equiaxial shape, with few visible fibers and smoother surfaces. It is worth remembering that fiberglass is used as reinforcement for the polymer in the manufacture of PCBs and, therefore, it is present in a significant percentage [16].



**Figure 1.** Morphology of the PCB residue by scanning electron microscopy. a) # 0.15 mm b) # 0.3 mm, c) # 0.6 mm, d) # 1.2 mm.

### 3.2 Compressive strength test

The results of the compressive strength test, at 28 days, are shown in Table 1. Except for the mortar with 5% of the residue retained in the 1.2 mm sieve, all other compositions presented compressive strength close to or above the reference value. The increase in the percentage of residue, from 5% to 10%, did not cause significant changes in the compressive strength, except for the mortar with residue retained in a 1.2 mm sieve. Analyzing only the compressive strength, it can be said that replacing up to 10% of the sand with residue is feasible.

In general, the best performance was observed for the mortar with residue retained in the 0.6 mm sieve. As observed in the microscopic analysis (Figure 1), in this range, the residue particles have a predominantly fibrillar shape, similar to the shape shown by the smaller ranges (0.15 mm and 0.3 mm), differing in terms of aspect ratio (ratio between diameter and fiber bundle length). The mortar penetrates between the fibers within the bundles improving its reinforcing effect in the mortar.

The reinforcing effect of fiberglass in the mortar was also observed by Mastali et al. [26], who found a gain in compressive strength with the insertion of this material.

It was not possible to establish a pattern of behavior for the particle size effect, since the variations in the results are small. Only the mortar with 5% of the residue retained in the 1.2 mm sieve showed a discordant behavior, value below average. Thus, it can be concluded that the particle size range of the residue had no influence on the results.

### 3.3 Water absorption, percentage of voids and density tests

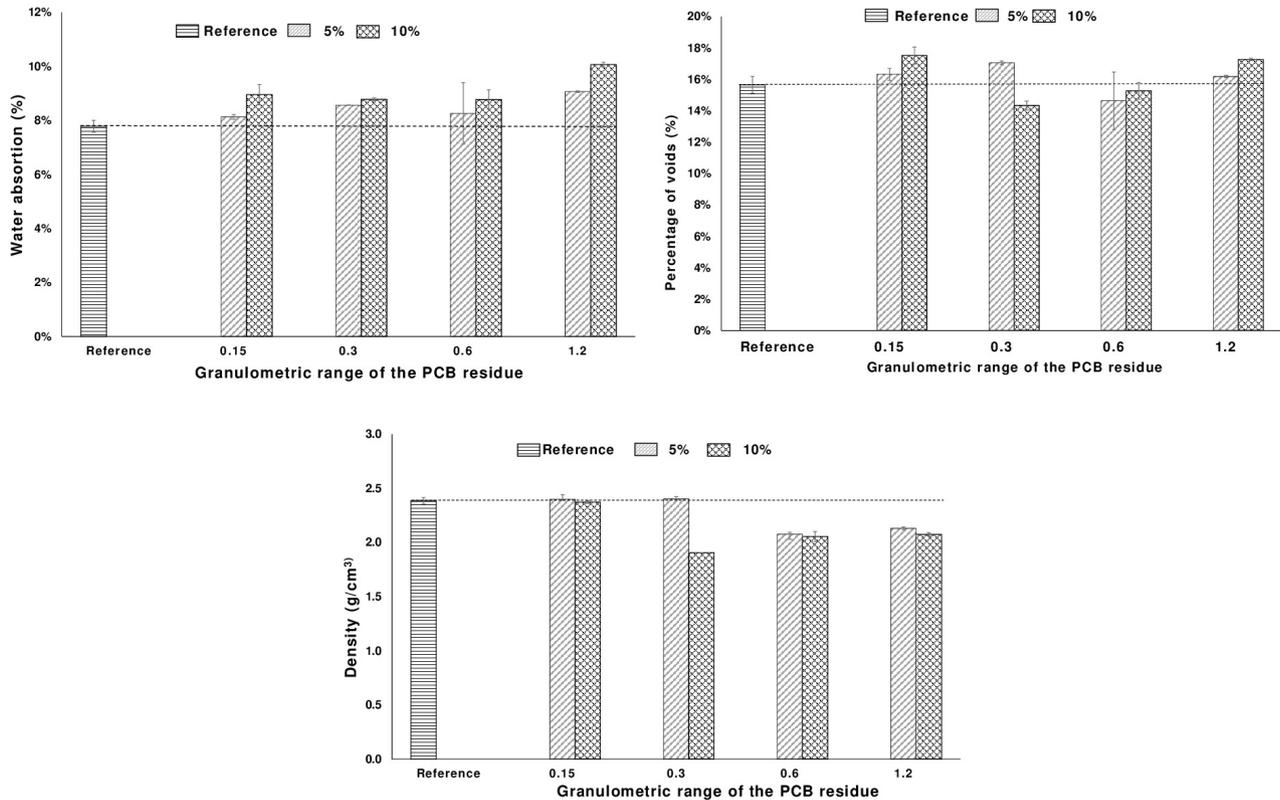
The test results for the determination of water absorption, percentage of voids and density are presented in Figure 2.

It was not possible to establish a pattern of behavior with the results of the water absorption and percentage of voids tests, either in relation to the increase in the percentage of waste (from 5% to 10%), or in relation to its particle size range. However, it is important to emphasize that the results are close to the reference mortar, in order to conclude that the incorporation of the residue does not significantly influence these properties.

In the density test, the mortars with the residue retained in the sieve of 0.15 mm (5% and 10%) and 0.3 mm (5%) presented results very close to the reference mortar;

**Table 1.** Results of compressive strength tests. Note: values in parentheses refer to the mean deviation

Compressive Strength (MPa)		Residue # 0.15 mm	Residue # 0.3 mm	Residue # 0.6 mm	Residue # 1.2 mm
Reference	32.4 (1.36)				
Mortar - 5%		32.93 (1.56)	32.81 (0.61)	35.32 (0.71)	28.99 (0.71)
Mortar - 10%		32.08 (0.50)	31.25 (0.51)	34.20 (0.06)	34.05 (0.54)



**Figure 2.** Comparative graphs of water absorption, percentage of voids and density test results.

for the other formulations there was a reduction in density. As residue unit weight, shown in Table 2, is smaller than sand unit weight, it is expected that, with the addition of the residue, there will be a reduction in mortar density. This reduction, however, varies according to residue particle size, as observed.

### 3.4 Analysis of the fracture surface of mortars by scanning electron microscopy

The fracture surfaces of mortars with 10% residue, after the compression test, were analyzed by SEM. Images are shown in Figure 3.

By analyzing the images, it can be seen that the residue is well homogenized in the mortar so that it is difficult to

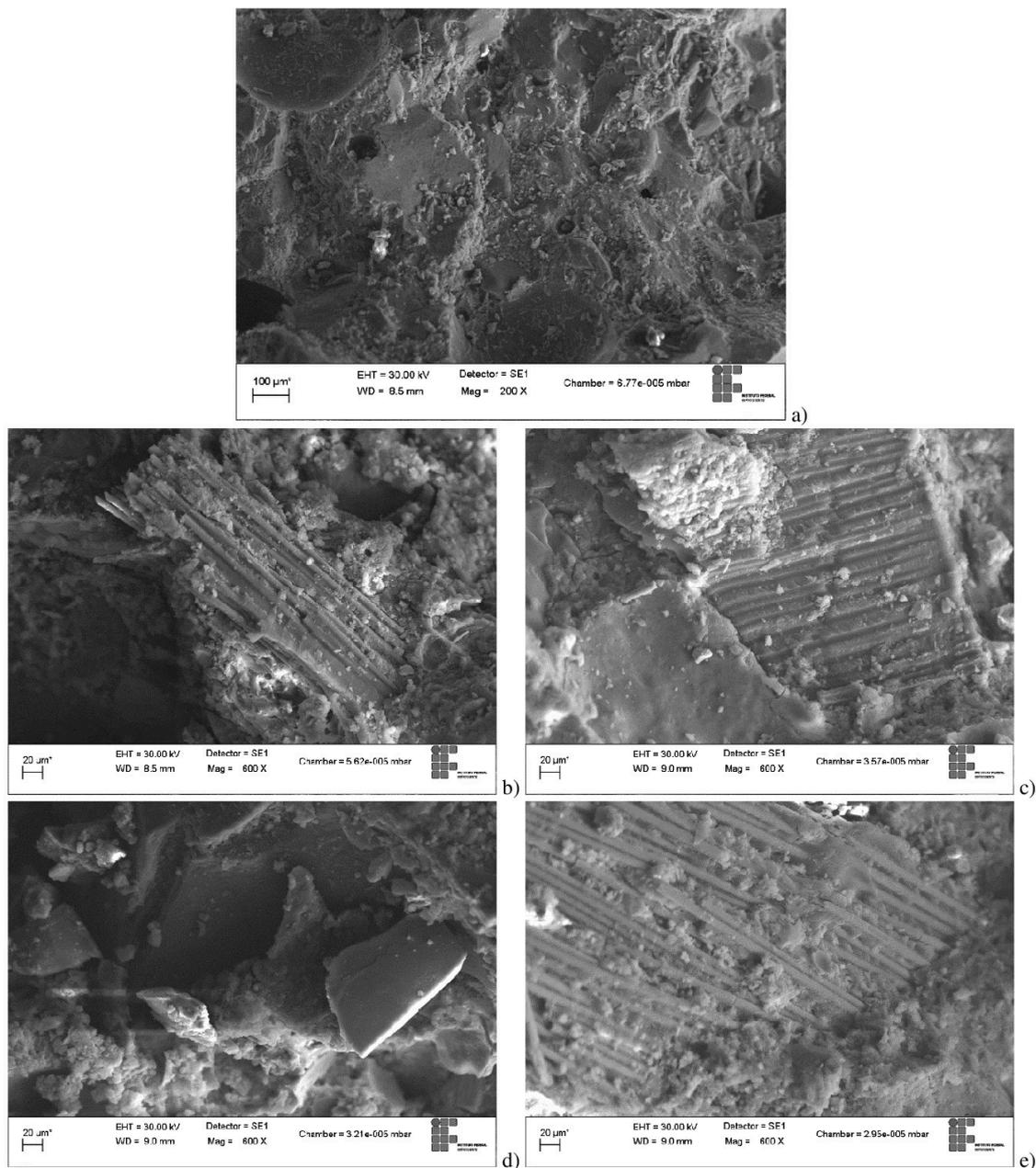
distinguish the residue from the paste, as it can be seen when comparing the reference mortar with the mortars that contain residue. Only fiberglass bundles, which have a very characteristic shape, can be identified more easily in the images. Note that the paste penetrates into the fiber bundles. In general terms, all mortars have the same characteristics, with pores of different sizes well distributed throughout the mortar, see Figure 3a.

### 3.5 Environmental tests

In the environmental classification tests, two samples were analyzed, both with 5% residue, one with residue retained in the 0.6 mm sieve and the other with residue retained in the 1.2 mm sieve. Both showed the same result. In the

**Table 2.** Unit weight of PCB residue and sand

	Sand	Residue # 0.15 mm	Residue # 0.3 mm	Residue # 0.6 mm	Residue # 1.2 mm
Unity weight (g/cm <sup>3</sup> )	1.448	0.433	0.568	0.675	0.614



**Figure 3.** Fracture surface of the mortars: a) reference, b) mortar # 0.15 mm, c) mortar # 0.3 mm, d) mortar # 0.6 mm, e) mortar # 1.2 mm.

leaching test, no parameter exceeded the maximum limits allowed by NBR 10005:2004 [27]. In the solubilization test, the concentration of total Barium and Phenols were above the maximum limit indicated in NBR 10004:2004 [17], classifying the material as Class II A, Non-hazardous waste and Non-inert.

As the mortar with 5% residue presented concentration of elements above the maximum limit indicated in NBR

10004:2004 [17], it is expected the same result for the mortar with 10% residue. The granulometry of the residue can influence the result of environmental tests. The mortars with thicker residue (# 0.6 mm and # 1.2 mm), were initially selected for the tests. If they were classified as “inert material”, which did not occur, the tests would be repeated for mortars with thinner residues in which, it is expected, the elements are more available for leaching and solubilization processes.

The fact of being classified as non-inert, requires control in the final disposal of the material.

#### 4 Conclusions

In general terms, all compositions of mortars with residue showed compressive strength close to or above the reference value. In the same way no significant change was observed in the percentage of voids or in the absorption of water. These properties vary, however it is not possible to establish a pattern of behavior regarding the effect of particle size or percentage of residue. On the other hand, the density was reduced for mortars with the thickest residue being below the reference mortar.

In the environmental analysis (leaching and solubilization tests), the mortar with residue was classified as Class II A Waste (Non-hazardous and Non-inert waste), for presenting

total Barium and Phenols concentration above the maximum limit indicated in NBR 10004:2004.

Based on the results, it can be stated that the residue of printed circuit boards has the potential to be used as a partial substitute for sand in the mortar in the percentages analyzed. However, the fact that it is classified as Non-inert requires control in the final disposal of the material.

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#### References

- 1 Forti V, Baldé CP, Kuehr R, Bel G. The Global E-waste Monitor 2020: quantities, flows, and the circular economy potential. 2020 [cited 2021 Apr 1]. Available at: <https://ewastemonitor.info/gem-2020/>
- 2 Ongondo FO, William ID, Cherrett TJ. How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Management (New York, N.Y.)*. 2011;31(4):714-730. <http://dx.doi.org/10.1016/j.wasman.2010.10.023>.
- 3 Filin S, Kalinina I, Maslennikov V, Ibraimova S, Velikorossov V, Chaikovskiy A. Management of electronic and electrical equipment waste collection in municipalities. In: *E3S Web of Conferences* 247. France: EDP Sciences; 2021. p. 01023. <http://dx.doi.org/10.1051/e3sconf/202124701023>.
- 4 Tanskanen P. Management and recycling of electronic waste. *Acta Materialia*. 2013;61(3):1001-1011. <http://dx.doi.org/10.1016/j.actamat.2012.11.005>.
- 5 Zhitong Y, Tung-Chai L, Sarker PK, Weiping S, Jie L, Weihong W, et al. Recycling difficult-to-treat e-waste cathode-ray-tube glass as construction and building materials: a critical review. *Renewable & Sustainable Energy Reviews*. 2018;81:595-604. <http://dx.doi.org/10.1016/j.rser.2017.08.027>.
- 6 Vazquez YV, Barbosa SE. Recycling of mixed plastic waste from electrical and electronic equipment. Added value by compatibilization. *Waste Management (New York, N.Y.)*. 2016;53:196-203. <http://dx.doi.org/10.1016/j.wasman.2016.04.022>.
- 7 Liu J, Yang T, Hu Z, Feng G. The development of unimolecular conjugated polymeric micelles for the highly selective detection and recovery of gold from electronic waste. *New Journal of Chemistry*. 2019;43(30):11811-11815. <http://dx.doi.org/10.1039/C9NJ02077B>.
- 8 Sun Z, Cao H, Xiao Y, Sietsma J, Jin W, Agterhuis H, et al. Toward sustainability for recovery of critical metals from electronic waste: the hydrochemistry processes. *ACS Sustainable Chemistry & Engineering*. 2017;5(1):21-40. <http://dx.doi.org/10.1021/acssuschemeng.6b00841>.
- 9 Akcil A, Erust C, Gahan CS, Ozgun M, Sahin M, Tuncuk A. Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixivants – a review. *Waste Management (New York, N.Y.)*. 2015;45:258-271. <http://dx.doi.org/10.1016/j.wasman.2015.01.017>.
- 10 Shen M, Ge J, Lam J, Zhu M, Li J, Zeng L. Occurrence of two novel triazine-based flame retardants in an E-waste recycling area in South China: implication for human exposure. *The Science of the Total Environment*. 2019;683:249-257. <http://dx.doi.org/10.1016/j.scitotenv.2019.05.264>.
- 11 He K, Sun Z, Hu Y, Zeng X, Yu Z, Cheng H. Comparison of soil heavy metal pollution caused by e-waste recycling activities and traditional industrial operations. *Environmental Science and Pollution Research International*. 2017;24(10):9387-9398. <http://dx.doi.org/10.1007/s11356-017-8548-x>.

- 12 Martínez AL, Barrera GM, Díaz CE, Córdoba LI, Núñez FU, Hernández DJ. Recycled polycarbonate from electronic waste and its use in concrete: Effect of irradiation. *Construction & Building Materials*. 2019;201:778-785. <http://dx.doi.org/10.1016/j.conbuildmat.2018.12.147>.
- 13 Siddiqui MN, Redhwi H, Antonakou EV, Achilias DS. Pyrolysis mechanism and thermal degradation kinetics of poly(bisphenol A carbonate)-based polymers originating in waste electric and electronic equipment. *Journal of Analytical and Applied Pyrolysis*. 2018;132:123-133. <http://dx.doi.org/10.1016/j.jaap.2018.03.008>.
- 14 Sommerhuber PF, Wang T, Krause A. Wood-plastic composites as potential applications of recycled plastics of electronic waste and recycled particleboard. *Journal of Cleaner Production*. 2016;121:176-185. <http://dx.doi.org/10.1016/j.jclepro.2016.02.036>.
- 15 Hadi P, Xu M, Lin CS, Hui CW, McKay G. Waste printed circuit board recycling techniques and product utilization. *Journal of Hazardous Materials*. 2015;283:234-243. <http://dx.doi.org/10.1016/j.jhazmat.2014.09.032>.
- 16 Medeiros NM. Caracterização e separação física de placas de circuito impresso de computadores obsoletos [thesis]. Natal: Universidade Federal do Rio Grande do Norte; 2015 [cited 2021 Oct 29]. Available at: <https://repositorio.ufrn.br/jspui/handle/123456789/20607>.
- 17 Associação Brasileira de Normas Técnicas. ABNT NBR 10004: resíduos sólidos – classificação. Rio de Janeiro: ABNT; 2004.
- 18 Alagusankareswari K, Sandeep Kumar S, Vignesh KB, Abdul Hameed Niyas K. An experimental study on e-waste concrete. *Indian Journal of Science and Technology*. 2016;9(2):1-5. <http://dx.doi.org/10.17485/ijst/2016/v9i2/86345>.
- 19 Premur V, Vučinić AA, Vujević D, Bedeković G. The possibility for environmental friendly recycling of printed circuit boards. *Journal of Sustainable Development of Energy, Water and Environment Systems*. 2016;4(1):14-22. <http://dx.doi.org/10.13044/j.sdewes.2016.04.0002>.
- 20 Gomathi Nagajothi P, Kala F. Compressive strength of concrete incorporated with e-fiber waste. *International Journal of Emerging Technology and Advanced Engineering*. 2014;4(4):23-27. <http://dx.doi.org/10.13140/RG.2.2.13814.91207>.
- 21 Huang HL, Hwang CL, Peng SS, Wang EH, Chen CT, Chiang CC. Assessing the adequacy of concrete mixes utilizing PCB powders. *Journal of Testing and Evaluation*. 2014;42(1):135-145. <http://dx.doi.org/10.1520/JTE20120218>.
- 22 Associação Brasileira de Normas Técnicas. ABNT NBR NM 45: agregados - determinação da massa unitária e do volume de vazios. Rio de Janeiro: ABNT; 2006.
- 23 Associação Brasileira de Normas Técnicas. ABNT NBR 7215: Cimento Portland - determinação da resistência à compressão de corpos de prova cilíndricos. Rio de Janeiro: ABNT; 2019.
- 24 Moncea AM, Badanoiu A, Georgescu M, Stoleriu S. Cementitious composites with glass waste from recycling of cathode ray tubes. *Materials and Structures*. 2013;46(12):2135-2144. <http://dx.doi.org/10.1617/s11527-013-0041-5>.
- 25 Associação Brasileira de Normas Técnicas. ABNT NBR 9778: argamassa e concreto endurecidos - determinação da absorção de água, índice de vazios e massa específica. Rio de Janeiro: ABNT; 2009.
- 26 Mastali M, Dalvand A, Sattarifarid A. The impact resistance and mechanical properties of reinforced self-compacting concrete with recycled glass fiber reinforced polymers. *Journal of Cleaner Production*. 2016;124:312-324. <http://dx.doi.org/10.1016/j.jclepro.2016.02.148>.
- 27 Associação Brasileira de Normas Técnicas. ABNT NBR 10005: procedimento para obtenção de extrato lixiviado de resíduos sólido. Rio de Janeiro: ABNT; 2004. 16p.

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