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Production of concrete paving blocks using electroplating waste – Evaluation of concrete properties and solidification/stabilization of waste

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Abstract. The determination of the effectiveness of the immobilization of blasting dust (waste generated in galvanic activities) in cement matrix, as well of mechanical, physical and microstructural properties of concrete paving blocks produced with partial replacement of cement was the objective of this work. The results showed that blasting dust has high percentage of silica in the composition and very fine particle size, characteristics that qualify it for replacement of cement in manufacturing concrete blocks. The replacement of Portland cement by up to 5% residues did not cause a significant loss in compressive strength nor increase in water absorption of the blocks. Chemical tests indicated that there is no problem of leaching or solubilization of contaminants to the environment during the useful life of the concrete blocks, since the solidification/stabilization process led to the immobilization of waste in the cement mass. Therefore, the use of blasting dust in the manufacture of concrete paving blocks is promising, thus being not only an alternative for proper disposal of such waste as well as a possibility of saving raw materials used in the construction industry.

Keywords: blasting dust; concrete paving block; stabilization; solidification

1. Introduction

Industrial activities are the main generators of waste both in quantity and in danger. Their waste, if managed incorrectly, constitutes one of the main causes of environmental and human health damages due to their toxicity and diversity of chemical composition.

Electroplating is a branch of the metalworking industry in which is performed the treatment of surfaces, metallic or otherwise, by depositing a thin layer of metal or alloy through electrolytic and chemical processes, giving a dense, uniform and adherent coating on the surface.

The solid waste generated in electroplating processes consist largely of dust and particulate

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metallic, ceramic or organic compounds, from the operations of mechanical pre-treatmentand finishing of parts during manufacture. Waste may also be derived from sludge from rinsing processes and also from sludge from the wastewater treatment system, which have a high concentration of heavy metals in their composition (Chen *et al*. 2011, Shopia and Swaminathan 2005).

Blasting dust is one of solid waste generated in the mechanical pre-treatment of pieces that will undergo the electroplating process. In this step, in a chamber there is the blasting of the parts with glass microspheres, an abrasive that remove impurities, roughness and irregularities on the surface of the parts.

During the mechanical cleaning, the microspheres are broken, generating dust which consists mainly of glass powder, metals and impurities from work pieces. This dust is collected, packaged and taken to landfills; it no longer has any use to galvanic industries.

With the growing demand for implementation of environmental policies grounded in sound management of wastes, industries are increasingly interested in ways to minimize waste generated, as well as the development of viable means for the reuse and stabilization thereof for safe final disposal.

The construction industry is one sector that has shown promise in the use of industrial waste through the development of new materials for their own consumption. Several studies have been and are being conducted to develop clean and viable techniques and technologies for reuse of waste.

This research area focuses on studying the incorporation/reuse of industrial wastes as raw materials for the manufacture of concrete such as Ismail and Al-Hashmi (2009), Chen *et al*. (2011), Kaur *et al*. (2013), Park *et al*. (2004), Topçu and Canbaz (2004) and Ahmadi and Al-Khaja (2001), or in the manufacture of concrete artifacts as studied by Chidiac and Mihaljevic (2011), Gencel *et al*. (2012) and Tavares and Franco (2012), aiming to reduce the demand for natural resources used by the construction industry, along with the necessity of reducing the environmental impact generated by the large amount of waste available.

One of the techniques used for the incorporation of waste in the construction industry is the stabilization/solidification in cement matrix. This process has been used as option for the treatment of different types of industrial wastes, especially for those containing high concentrations of heavy metals (Chaudhary and Malviya 2006, John *et al*. 2011, Gollmann *et al*. 2010, Asavapisit 2004, Shopia and Swaminathan 2005).

According to Shi and Spence (2004) and USEPA (2009), solidification refers to a process that binds the contaminated medium with a reagent/binder, changing its physical properties and increasing the mechanical properties such as compression strength, reducing permeability and encapsulating contaminants to form a solid material. The stabilization refers to a process involving a chemical reaction that reduces the leaching of hazardous waste immobilizing chemical components and decreasing solubility, making them less harmful.

The techniques of stabilization/solidification besides being used in construction for promoting stabilization of hazardous waste, rendering them inert, also contribute to the economy of raw materials used, thus minimizing environmental damage and the extra costs incurred.

In this context, this study aimed to incorporate solid galvanic waste, blasting dust, in the manufacture of concrete paving blocks for partial replacement of cement. Also, it was investigated physical, chemical, mechanical, and microstructural characteristics of concrete blocks manufactured with such residue, as well as the efficiency of stabilization/solidification of contaminants in the cement matrix.

2. Research motivation

2.1 Collection and characterization of the waste

The electroplating waste (blasting dust) used for the manufacture of concrete paving blocks was collected directly from generating industries, located in Maringá - Paraná State - Brazil. After collection, the waste was wrapped in plastic containers and stored in a sheltered place.

The physical characterization of the residue was performed by integrated particle size analysis (laser granulometer Cilas 1064 between 0.04 and 500 μm). Chemical characterization was performed by x-ray fluorescence analysis (x-ray Spectrometer Rigaku, model ZSX Mini II), determination of metals (Atomic Absorption Spectrometer Varian - Spectraa-240FS) with sample digestion using methods of USEPA 3052 (1996), leaching and solubilization according to the Brazilian Standards NBR 10005 (2004) and NBR 10006 (2004), respectively.

The procedure for the leaching test consists in maintaining 50 g sample of the dried and sieved material into contact with 1 liter of acid solution (acetic acid) for 18 hours under stirring rotating at 30 rpm and 25°C.

The solubilization test according to the Brazilian Standard NBR 10006 (2004) is based on the contact of a mixture of 250 g sample of the dried and sieved material with 1 liter of deionized water for 7 days at 25°C. After a period of testing, the leached and solubilized samples are subjected to vacuum filtration through a membrane of 0.45 μm and stored in vials.

Both the leached and solubilized extract of the waste were subjected to tests to determine the levels of contaminants listed in Annexes F and G of the standard NBR 10004 (2004). To this were used Varian Atomic Absorption Spectrometer - SPECTRAA-240FS and ion Chromatograph, Metrohm - 850 Professional IC.

2.2 Fabrication and characterization of concrete paving blocks

2.2.1 Material

The cement used in the manufacture of the specimens was Portland cement CP V - ARI with high early strength. Table 1 lists some characteristics of this type of cement available by the manufacturer.

Table 1 Characteristics of the binder (CP V – ARI)

Chemical composition (% mass)					
Al_2O_3	SiO_2	K_2O	CaO	Fe_2O_3	SO_3
1.16	7.97	1.28	80.92	5.50	0.73
Complementary characteristics					
200 mesh (%)	Blaine ($cm^2.g^{-1}$)	Hot expansion (mm)	Water (%)	Star of setting (min)	End of setting (min)
0.30	5100.00	0.00	28.00	160.00	270.00
Compressive strength (MPa)					
24 hours	3 days	7 days	28 days		
28	39	44	51		

Source: Intercement (2011)

The fine aggregate used to manufacture concrete blocks was medium sand with particle size between 0.20 mm and 0.60 mm, fineness modulus of 1.74; maximum characteristic dimension of 1.20 mm and density of 2.66 $kg.dm^{-3}$. The coarse aggregate used was gravel with a grain size between 2.40 mm and 9.50 mm, fineness modulus of 5.97, maximum characteristic dimension of 9.50 mm, density of 2.01 $kg.dm^{-3}$ and absorption of 6.49%. Both aggregates were within specification limits from the Brazilian Standard NBR 7211 (2009) for the manufacture of Portland cement concrete.

The water used in concrete mortar was that available to supply the city of Maringá – Paraná State, provided by the Companhia de Saneamento do Paraná (SANEPAR).

2.2.2 Composition and manufacture

Besides the use of the binder, aggregates and water, concrete paving blocks were manufactured with different proportions of waste to replace cement. The proportions used were 2%, 3%, 4%, 5% and 10% residue (dry weight). Table 2 shows the different compositions used in the manufacture of concrete.

Concrete blocks were produced in a semi-automatic pneumaticvibro-press with capacity ofproducing eight blocks per cycle. The unmolding of blocks was performed on wooden pallets and cure took place in moist chamber until reaching the ages determined for characterization tests. Pavements produced were 100 mm (width) × 200 mm (length) × 80 mm (height).

2.2.3 Tests conducted on specimens

To evaluate the performance of pavements made with different percentages of blasting dust to replace cement, including the ability of solidification / stabilization of waste in the cement matrix, the specimens were subjected to mechanical, physical, chemical and microstructural characterization.

The mechanical characterization was performed by testing for compressive strength. The tests were conducted according to the recommendations of the Brazilian Standard NBR 9781 (2013), using hydraulic press. Six specimens were broken at curing age of 28 days, for each percentage of replacement. The compressive strength test consists of applying a compressive load to the concrete block using a hydraulic press to simulate the maximum stress that the blocks bear up to rupture. The compressive strength (MPa) of the specimens were obtained by dividing the failure load (N) by the area of load application (mm^2).

Table 2 Composition of concrete paving blocks manufactured with blasting dust

Percentage of replacement	w/b	C	S	BD	G
Ref.	0.38	1.00	2.65	0.00	1.35
2%	0.38	0.98	2.65	0.02	1.35
3%	0.38	0.97	2.65	0.03	1.35
4%	0.38	0.96	2.65	0.04	1.35
5%	0.38	0.95	2.65	0.05	1.35
10%	0.38	0.90	2.65	0.10	1.35

Ref.: specimen without addition of waste; w/b: water/binder ratio; C: cement; S: sand; BD: blasting dust; G, gravel

The physical characterization of concrete block was by means of water absorption tests, which were based on the methodology prescribed by the Brazilian Standard NBR 9781 (2013). In the tests, we employed three specimens at curing age of 28 days. The water absorption is calculated from the difference between the mass of the block immersed in water at 23 ± 5°C for 24 hours (m_2) and the mass of the block dried at 110 ± 5°C for 24 hours (m_1). Eq. (1) shows the calculation of water absorption (A) in percentage

$$A = \frac{m_2 - m_1}{m_1} \times 100 \tag{1}$$

The microstructural characterization was carried out by x-ray diffraction analysis at the curing age of 28 days using equipment model Bruker-AXS, D8 Advance. Leaching and solubility analysis (chemical characterization) were also held at 28 days of curing to verify the effectiveness of the stabilization / solidification of the waste in the cement matrix. These analyses were accomplished according to the methodologies set by Brazilian Standards NBR 10005 (2004) and ABNT NBR 10006 (2004), respectively. Both methods are based on the 1311 U.S EPA SW-846 method.

The results were statistically analyzed by analysis of variance (ANOVA), Tukey's test and scatter plots with calculation of Pearson's correlation coefficient (r) to determine a possible correlation between variables. It was also performed a significance test on the r determined, together with the corresponding sample size (n), at a significance level of $\alpha = 0.01$, in order to determine if indeed there is a linear correlation between the variables.

3. Results and discussion

The results of the particle size distribution of the blasting dust in Table 3 show a particle size

Table 3 Particle size analysis of the electroplating waste

Sieve (mm)	Blasting dust	
	Retained (%)	Cumulative retained (%)
0.090	4.19	4.19
0.075	6.51	10.70
0.063	9.90	20.60
0.053	11.41	32.01
0.043	12.08	44.09
0.036	8.11	52.20
0.028	9.73	61.93
0.020	11.15	73.08
0.010	13.27	86.35
0.006	4.52	90.87
0.003	3.75	94.62
0.001	4.26	98.88
Bottom	1.12	100.00

Table 4 Chemical composition of the electroplating waste

Compounds		Elements	
Chemical composition	(% mass)	Metals	Concentration (mg.kg^{-1})
MgO	6.68	Al	15,786.00 ± 3.0
Al_2O_3	1.15	Ba	3,438.50 ± 0.5
SiO_2	67.86	Cd	6.35 ± 0.0
P_2O_5	0.33	Pb	178.10 ± 0.1
K_2O	1.43	Cu	2,277.10 ± 0.8
CaO	16.11	Cr	126.40 ± 0.0
Fe_2O_3	1.03	Fe	4,631.60 ± 1.6
ZnO	0.17	Mn	34.80 ± 0.0
SO_3	0.28	Ag	0.55 ± 0.0
Cl	0.05	Na	113,832.80 ± 31.4
SrO	0.03		
CuO	0.57		
CdO	0.06		
Na_2O	4.26		

distribution between the ranges 0.001-0.09 mm with an average particle diameter of around 0.0038 mm or 3.80 μm. This waste can be considered as very thin as about 90% of particles are below the diameter of 0.075 mm, with about 56% of the material smaller than 0.045 mm (45.00 μm). The blasting dust can also be classified according to the International Society of Soil Mechanics and Foundation Engineering (ISSMFE) in the particle size range typical of silt, ranging from 0.002 mm to 0.06 mm.

The blasting dust has particle diameters within the range of fly ash (particles < 0.001 mm to 0.10 mm), blast furnace slag (particles < 0.045 mm) and rice husk ash (0.012 mm average particle diameter). The foregoing materials are considered substitutes for mineral compounds to be added to Portland cement concrete, once they act as pozzolanic materials in cement paste, favoring resistance to thermal cracking and increased ultimate strength, impermeability and durability of concrete, as noted by Mehta and Monteiro (2013).

Table 4 presents the results of the chemical analysis of the blasting dust.

Among the chemical compounds in the waste composition stands out the percentage of SiO_2, 67.86%. It was also observed significant amounts of CaO (16.10%), MgO (6.70%), Na_2O (4.30%), K_2O (1.40%) and other compounds in amounts less than 1.00%. Alkalis, according to the observations of Mehta and Monteiro (2013) may cause deterioration of the concrete by means of expansive reactions (alkali-aggregate reactions), resulting in deformation, displacement of the structure, cracking, spalling, and popping of concrete.

The blasting dust complies with the chemical requirements prescribed by the Brazilian Standard NBR 12653 (1992) for its classification as pozzolanic material Class N, presenting sum of oxides ($SiO_2 + Al_2O_3 + Fe_2O_3$) around 70.00% and percentage of sulfur trioxide (SO_3) of 0.28%. That standard also limits the amount of Na_2O equivalents ($Na_2O + 0.658K_2O$) in pozzolanic materials at 1.50%. The blasting dust presented amount of available alkali of 5.20%, indicating its moderate use to replace cement in order to prevent damages to the concrete structure.

Table 5 Concentration of contaminants in the extract leached from the electroplating waste

Contaminant	Limit NBR* ($mg.L^{-1}$)	Blasting dust ($mg.L^{-1}$)
Ba	70.00	N.D.
Cd	0.50	0.08
Pb	1.00	1.19
Cr	5.00	0.18
Hg	0.10	N.D
Ag	5.00	0.13
Fluoride (F^-)	150	N.D.

* Limit of the Brazilian Regulatory Standard ABNT NBR 10004 (2004)
N.D. – not detected (values below the detection limit of the analysis equipment)

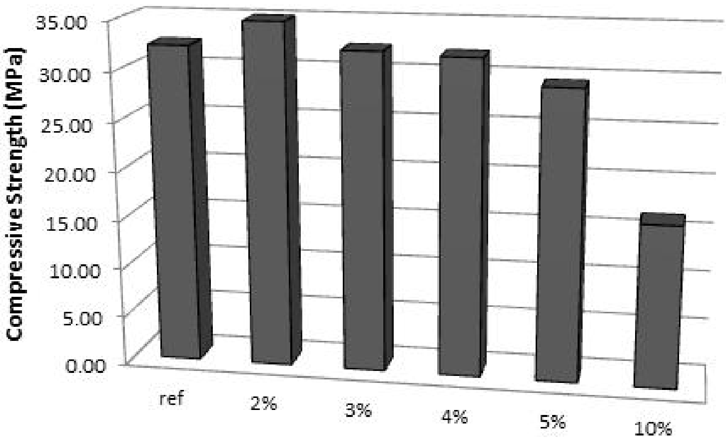

Fig. 1 Characteristic compressive strength of concrete paving blocks with blasting dust

The average results of metal concentration in the blasting dust samples are also listed in Table 4. Sodium (Na) and aluminum (Al) were metals with higher concentrations in dry weight in the samples of the waste. The high concentrationof these metalscan beexplained by thecomposition of theglass microspheres. In addition to thesilica (SiO_2) its main component, the glass also hasin its compositioncarbonates, sulfates and oxides ofsodium (Na_2CO_3, Na_2SO_4, Na_2O), and aluminum oxide(Al_2O_3) responsible for the mechanical strenght of the glass.

Iron (Fe), barium (Ba) and copper (Cu) also showed considerable concentrations in the matrix of blasting dust. These metals are related to the composition of the metal parts subjected to electroplating process.

The leaching and solubilization are used to extract substances present in the solid components through dissolution in a solvent. The standard ABNT NBR 10004 (2004) uses these operations as a means to classify hazardous solid waste.

Table 5 shows the average concentrations of contaminants obtained from the leaching test of the electroplating waste, as well as the limits stipulated by the Annex F of the standard abovementioned.

The blasting dust presented a concentration of lead (Pb) above the maximum stipulated in the standard (Table 5). The presence of a metal in the leachate extract at concentrations above the permissible limits, results in classifying the blasting dust as solid waste Class I - Dangerous.

Fig. 1 and Table 6 illustrates the results relative to the test of compressive strength at which the concrete paving blocks produced with blasting dust were subjected to. Table 7 shows the results of ANOVA for compressive strength tests obtained after 28 days of curing. Analysis of variance was run to evaluate the statistical difference between the mean values of treatments.

ANOVA evidenced a significant difference between the six treatments. As the p-value is lower than 0.01, the mean values of compressive strength are different to each other at 1% probability, or at least one mean value is different from the others with a confidence level limit of 99%.

To know which mean values are significantly different, a Tukey's test was run (Table 8).

Table 8 shows the average compressive strength for the reference blocks and blocks produced with 2%, 3%, 4%, 5% and 10% waste, as well as the results of the Tukey's test at 1% probability. No significant differences was found between the mean compressive strength of reference blocks (ref.) and those of the blocks produced with 2%, 3%, 4% and 5% waste, however the mean value of the blocks with 10% blasting dust was lower than and significantly different from the others in a confidence limit of 99%. These results indicate the possibility to use up to 5% blasting dust in manufacturing concrete paving blocks without significant loss of strength.

The results also showed a tendency to decrease the resistance of concrete blocks associated

Table 6 Mean values of compressive strength

Blocks	Ref.	2%	3%	4%	5%	10%
Compressive strength (Mpa)	32.38	34.94	32.33	32.01	29.41	16.49

Table 7 ANOVA for compressive strength values

Source of variation	Degrees of freedom	Sum of squares	Quadratic mean	F	P-value
Treatments	5	1328.83	265.77	20.92	0.00*
Error	29	368.45	12.71		
Total	34	1697.28			

*Significant at 1% probability (P-value < 0.01)

Table 8 Tukey's test for compressive strength values (MPa)

Treatment	Mean value
Ref	32.38 a
2%	34.94 a
3%	32.33 a
4%	32.01 a
5%	29.41 a
10%	16.49 b

Obs.: Mean values followed by the same letter are not significantly different at 1% probability by Tukey' test with the addition of residue. According to Benson *et al*. (1986) and Zain *et al*. (2004), this drop in resistance can be attributed to retardation of cement hydration due to the presence of heavy metals in blasting dust composition. The high pH of cementitious means causes precipitation of the metal ions in the form of oxides, hydroxides and carbonates which deposit on the surface of the cement grains, causing retardation of hydration and resulting in the decreased resistance.

According to the Brazilian Standard NBR 9781 (2013), the minimum strength required for concrete paving blocks for use in light vehicle traffic routes should be ≥ 35.00 MPa. It can be observed in Fig. 1 and Table 6 that none of the manufactured blocks including the reference reached the minimum strength stipulated by the regulation.

This behavior may be related to the water/binder ratio (0.38) used in the manufacture of the blocks, which was low compared with other studies. Tavares and Franco (2012) studied the incorporation of blasting dust into concrete paving blocks, Park *et al*. (2004) studied the incorporation of glass waste with different particle sizes into concrete artifacts. Both achieved compressive strength values of fabricated parts exceeding 35.00 MPa using water/binder ratio of 0.40 and 0.47, respectively.

The water absorption is another feature of utmost importance in evaluating the quality of concrete blocks. It is a property directly related to the durability of the material. Very porous blocks, resulting from hydration reactions, have more voids and absorb more water, are less resistant and can leach chemicals harmful to the environment.

Fig. 2 and Table 9 shows the mean values for the water absorption test for the concrete blocks manufactured.

In general, values of water absorption of the blocks remained within the maximum percentage of absorption required by the NBR 9781 (2013), 6.00%. The exception was made for blocks with 10% waste that showed values higher than required by law in all curing ages studied. Table 10

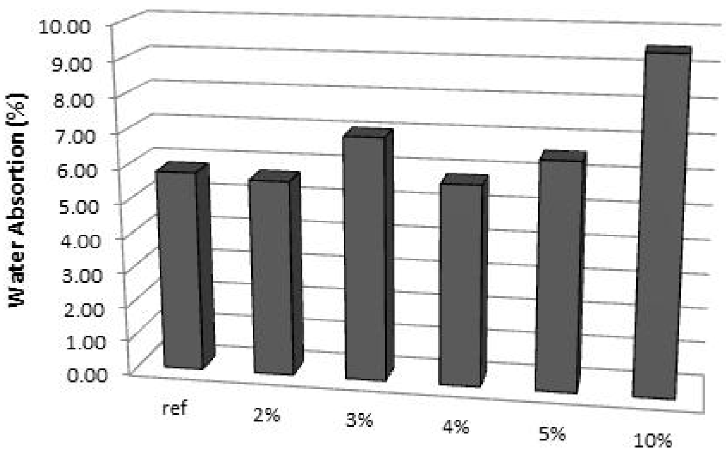

Fig. 2 Water absorption of concrete paving blocks manufactured with blasting dust

Table 9 Mean values of water absorption

Blocks	Ref.	2%	3%	4%	5%	10%
Water absorpion (%)	5.80	5.66	7.00	5.79	6.56	9.52

Table 10 ANOVA for water absorption

Source of variation	Degrees of freedom	Sum of squares	Quadratic mean	F	P-value
Treatments	5	31.33	6.27	4.7958	0.0143*
Error	11	14.37	1.31		
Total	16	45.70			

* Non-significant at 1% probability (P-value > 0.01)

shows the ANOVA for the water absorption of blocks after 28 days of curing.

The analysis of variance for the mean values of water absorption (Table 10) pointed out no significant difference at 1% level between treatments (*p*-value > 0.01), that is, there is a strong evidence that the partial replacement of fine aggregates by blasting dust did not significantly influence the values of water absorption of the blocks.

Although the water absorption values had no significant difference (Fig. 2), for quantities higher than 5% replacement of cement by waste it was observed an increase in water absorption values. These results are similar to those found by Chidiac and Mihaljevic (2011) and Taha and Nounu (2008), who studied the use of waste glass powder in the manufacture of concrete blocks and hardened concrete, respectively. The authors attributed the increased absorption of water to a change in the products from hydration and in the microstructure of the concrete when glassy residues are added thereto.

Fig. 3 shows the scatter plot to verify the correlation between the tests of compressive strength and water absorption using a confidence level of 99%.

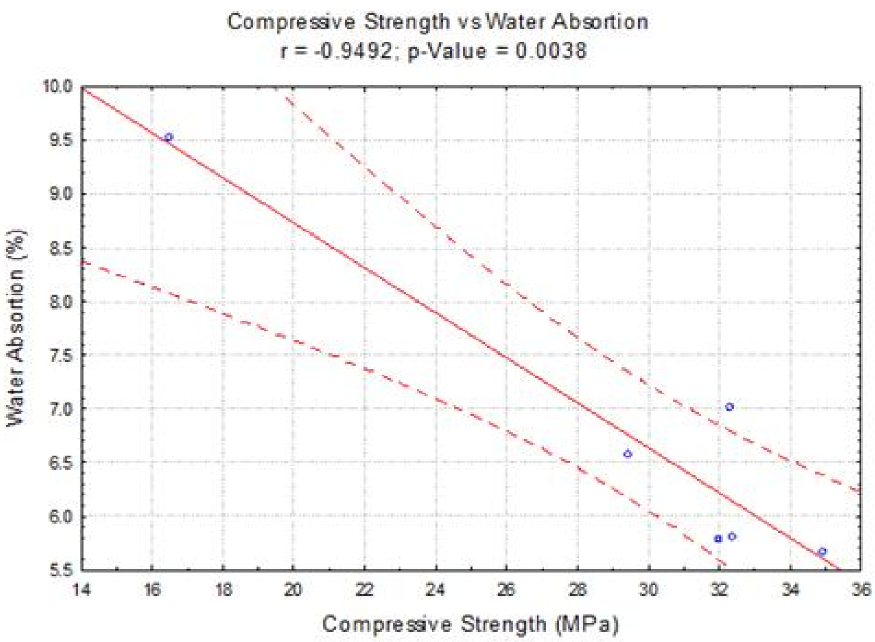

Fig. 3 Scatter plot for water absorption vs. compressive strength

The Pearson coefficient for compressive strength and water absorption was -0.94, which indicates a strong negative correlation. In accordance with the decision criterion to know the significance of r, the absolute value of r found (0.9492) must be higher than tabulated value (r = 0.917; for n = 6) at significance level α = 0.01 to exist a correlation. Thus, as 0.9492 > 0.917 the variables of compressive strength and water absorption are correlated, i.e., the increase of a variable indicates the decrease of the other.

According to the correlation, with increasing compressive strength there is a tendency to decrease water absorption in concrete blocks. According to Mehta and Monteiro (2013), this is a trend in hydraulic materials and is related to the porosity of the concrete paste. Stegemann and Buenfeld (2003) found similar results for these variables when evaluated the behavior of the compressive strength in relation to age of the concrete samples, ambient temperature and humidity.

Fig. 4 exhibits the results of the x-ray diffraction analysis in samples of the reference block and of blocks manufactured with waste. The main peaks were identified and crystalline compounds are listed in Table 11.

The x-ray diffraction analysis showed the presence of Ca $(OH)_2$ in the diffractogram of the reference block, especially for the peak at 37°2θ. In the diffractograms of the blocks added with 2%, 3%, 4%, 5% and 10% blasting dust was observed a marked reduction in the intensity of these peaks.

This behavior suggests the occurrence of consumption of calcium hydroxide from the hydration of the cement, in pozzolanic reactions with the silica (SiO_2) present in large amounts in the composition of the waste, forming secondary C-S-H ($2SiO_2.3CaO.3H_2O$). A similar result was found by Duart (2008) studying the microstructure of concrete with addition of rice husk ash.

Diffractograms also indicated an increase in the appearance of C-S-H peaks in blocks manufactured with blasting dust, corroborating the occurrence of pozzolanic reactions.

Table 11 Crystalline compounds present in the structure of the blocks made from blasting dust

Number	Compounds
1	SiO_2
2	$Ca(OH)_2$
3	CaO
4	$3CaO.SiO_2$
5	$2CaO.SiO_2$
6	$4CaO.Al_2O_3.H_2O$
7	$3CaO.Al_2O_3.H_2O$
8	$CaSO_4.H_2O$
9	$3CaO.Al_2O_3.2CaSO_4.31H_2O$
10	$CaO.Al_2O_3.Fe_2O_3$
11	$SiO.Al_2O_3$
12	$2SiO_2.3CaO.3H_2O$ (C-S-H)

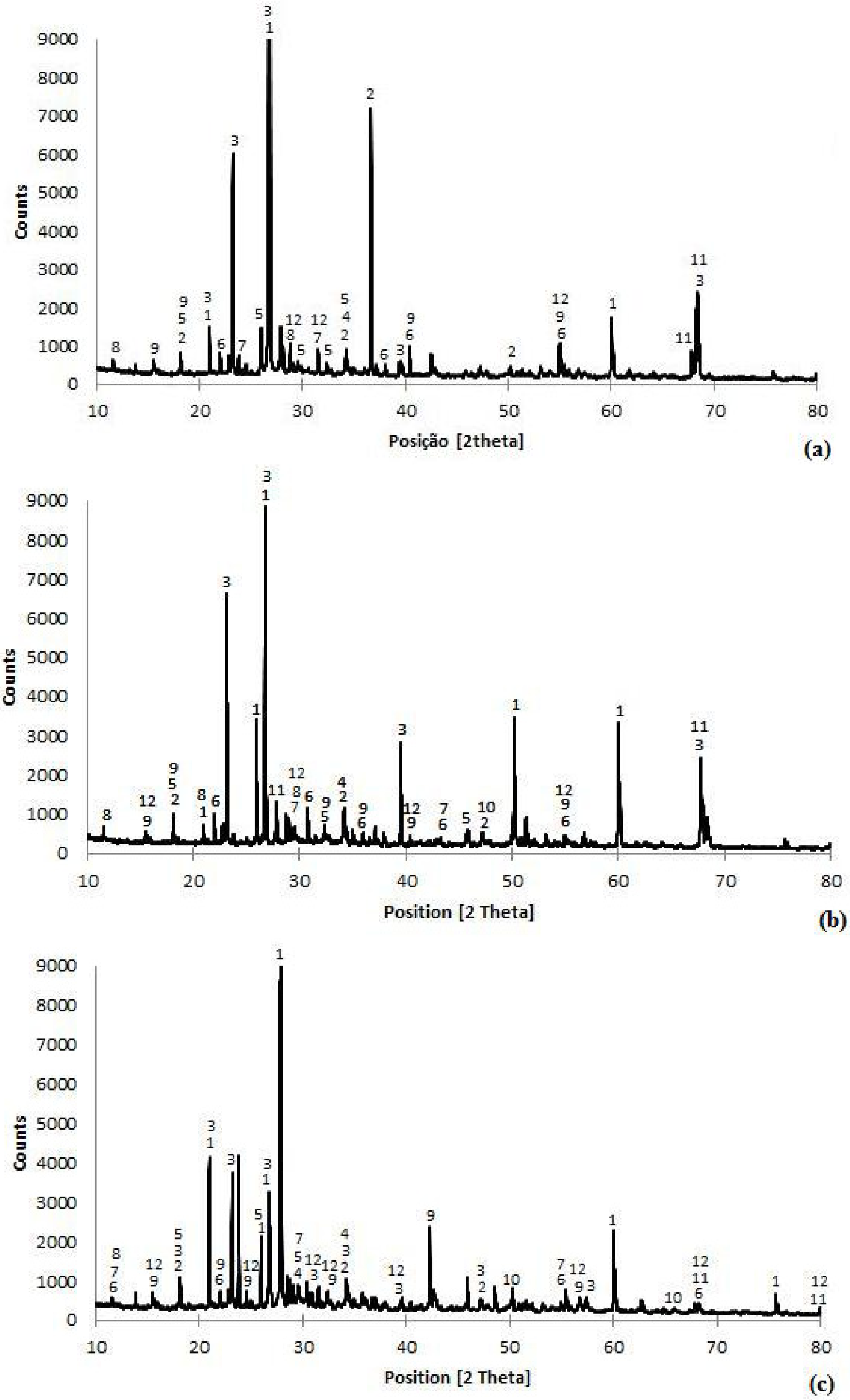

Fig. 4 Diffractograms of concrete block samples manufactured with blasting dust: (a) reference block; (b), (c), (d), (e), (f) blocks manufactured with 2%, 3%, 4% and 5% of electroplating waste, respectively

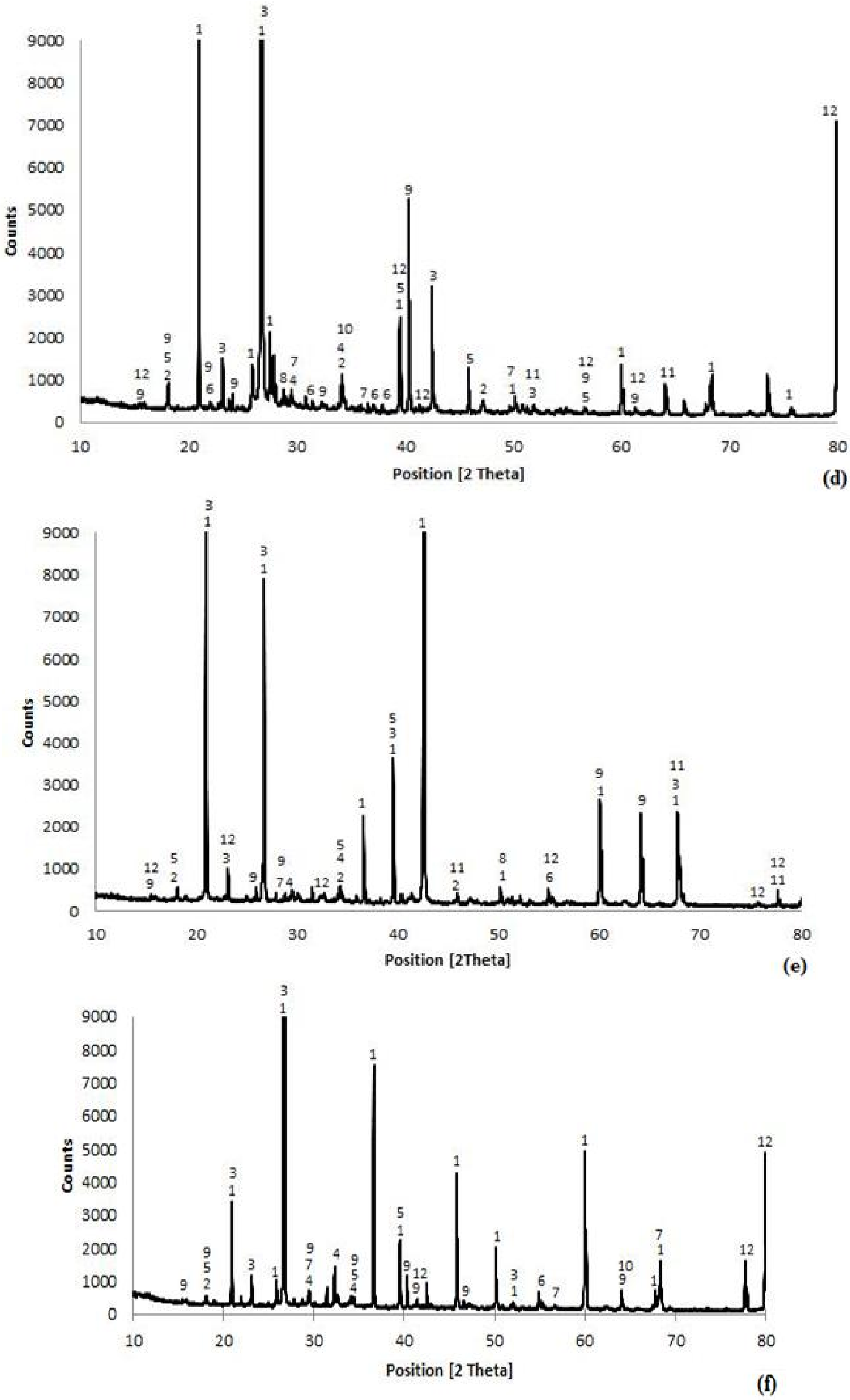

Fig. 4 Continued

Table 12 Concentration of contaminants in the leachate extract from samples of blocks with 28 days of curing

Contaminant	Limit NBR* ($mg.L^{-1}$)	Ref.	2%	3%	4%	5%	10%
Ba	70.00	48.44	63.04	59.23	64.65	64.03	64.05
Cd	0.50	0.02	0.03	N.D.	N.D.	0.03	0.02
Pb	1.00	0.24	0.26	0.21	0.24	0.32	0.27
Cr	5.00	0.36	0.40	0.37	0.38	0.36	0.34
Hg	0.10	N.D	N.D	N.D	N.D	N.D	N.D
Ag	5.00	0.05	0.05	0.05	0.05	0.02	0.02
Fluoride (F^-)	150	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

* Limit of the Brazilian Regulatory Standard ABNT NBR 10004 (2004)
N.D. – not detected (values below the detection limit of the analysis equipment)

Table 13 Summary of ANOVA for leaching

Source of variation	Degrees of freedom	Sum of squares	Quadratic mean	*F*	*P*-value
Ba	5	409.57	81.91	1.3886	0.3468
Cd	5	0.0014	0.0028	3.4679	0.0812
Pb	5	0.0133	0.0026	30.092	0.0003*
Cr	5	0.0048	0.0009	14.760	0.0026*
Ag	5	0.0026	0.0005	80.235	0.0000*

* Significant at 1% probability (*P*-value < 0.01)

Diffractograms of Fig. 4 also showed an increased occurrence of silica peaks in blocks produced with blasting dust, probably due to the addition of the waste. There are peaks typical of substances present in the composition of the cement (unhydrated clinker) as CaO, $3CaO.SiO_2$ (alite), $2CaO.SiO_2$ (belite), $CaO.Al_2O_3.Fe_2O_3$ (iron-aluminate) and $CaSO_4.H_2O$ (gypsum), besides peaks identified as products from the cement hydration as hydrated calcium aluminates ($4CaO.Al_2O_3.H_2O$ and $3CaO.Al_2O_3.H_2O$) and ettringite ($3CaO.Al_2O_3.2CaSO_4.31H_2O$).

Table 12 lists the results of leaching tests on concrete paving blocks with 28 days of curing.

None of the evaluated metals were found in the leachate extract with values above those set in NBR 10004 (2004) (Table 12). These results allow us to infer that the concrete paving block incorporating blasting dust will not cause problems of environmental contamination during use in paving and also that after the useful life, when discarded, should be classified as Class II waste – non-hazardous.

Metals present in the cement used in the manufacture of concrete blocks may have contributed significantly to the increased presence of barium and chromium in the leachate extract.

Table 13 shows a summary of the analysis of variance for the mean concentrations of metals leached presented in Table 12.

Through statistical analysis it was observed no significant difference between the mean concentrations of the metals barium and cadmium present in the leachate of reference blocks and blocks produced with waste at 1% probability.

Table 14 Concentration of contaminants in the solubilized extract in samples of BCP with 28 days of curing

Contaminant	Limit NBR (mg.L^{-1})	Ref.	2%	3%	4%	5%	10%
Al	0.20	N.D.	N.D.	N.D.	N.D.	N.D.	1.58
Cd	0.005	0.03	0.02	0.04	0.01	0.01	0.02
Pb	0.01	0.19	0.26	0.15	0.14	0.13	0.14
Cu	2.00	0.03	0.03	0.02	0.02	0.03	0.02
Cr	0.05	0.02	0.09	0.09	0.07	0.07	0.15
Fe	0.30	0.17	0.17	0.08	0.05	0.03	0.08
Mn	0.10	0.02	0.03	0.04	0.03	0.02	0.03
Hg	0.001	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ag	0.05	0.02	0.01	0.02	0.012	0.01	0.02
Na	200	43.09	22.84	23.43	41.61	27.37	18.31
Chloride (Cl^-)	250	1.56	N.D.	N.D.	N.D.	N.D.	N.D.
Fluoride (F^-)	1.50	0.13	N.D.	N.D	N.D.	N.D.	N.D.
Nitrate (NO_3^-)	10.00	15.17	N.D.	N.D.	N.D.	N.D.	N.D.
Sulfate (SO_4^{2-})	250	91.14	46.74	45.49	80.72	53.11	N.D.

* Limit of the Brazilian Regulatory Standard ABNT NBR 10004 (2004)
N.D. – not detected (values below the detection limit of the analysis equipment)

For the other metals there was evidence of differences between the mean concentrations in the leachate from reference blocks and blocks manufactured with waste, but even though this difference was statistically significant it did not change the characteristics of dangerousness of the leachate extract. These results evidence that the use of blasting dust did not significantly affect the leaching of metals.

Table 14 shows the results of solubility tests. The solubility test sets conditions required to differentiate wastes Class II A - not inert from wastes Class II B – inert.

Cadmium, lead and chromium were solubilized at concentrations above the limits of that standard, in blocks incorporating 2%, 3%, 4%, 5% and 10% waste. In solubilized extract of the reference block there was an excessive solubility of the ion nitrate (NO_3^-), but in the other samples this contaminant was not detected. These results allow classifying the wastes of concrete paving blocks, incorporated with blasting dust as Class II A - non-hazardous, non-inert.

The results of the leaching and solubility tests also enabled to check the efficiency of the solidification/stabilization of waste in the cement matrix. As observed, despite having characteristics that classify it as hazardous solid waste, blasting dust appears to have been fully incorporated into the concrete mass during the manufacture of the blocks, leading to a change in the characteristics of dangerousness.

This change in the hazardousness of the waste and in concentrations of contaminants present in the leachate extract of blocks produced with the waste in comparison to the reference block suggests that the solidification/stabilization process was capable of effectively immobilize metals in the cement mass.

Therefore, it is possible to conclude that the metals contained in the blasting dust used in partial replacement of cement in concrete mass, remain immobilized in the cement material, with no harm or risk of future contamination of the environment during and after its lifetime.

4. Conclusions

Our results showed the potential use of blasting dust in the manufacture of concrete paving blocks, using the technique of solidification/stabilization of the waste in the cement matrix.

It was possible to replace up to 5% cement by blasting dust without causing significant losses in mechanical and physical properties of blocks. Furthermore, the inertness and chemical stability of the residue was ensured through the efficient immobilization of contaminants in the cement matrix, reducing the leachability and hazardousness, resulting in blocks with good durability and within the environmental standards.

The results also indicated the interaction between the cement matrix and the residue through the extra formation of hydrated calcium silicates (C-S-H), one of the main constituents responsible for the mechanical strength of the concrete, from the reaction between silica of the blasting dust and calcium hydroxide from cement hydration reactions.

Thus, the blasting dust presented characteristics and behavior in cement matrices that allow classifying it as industrial solid waste that can be used as raw material in the construction industry, emerging as an alternative of reuse and inertization of waste deemed hazardous to the environment, and contribute to the economy of binder.

However, for the reuse of this waste is effectively carried out, there must be a joint effort between university, industry of interlocking blocks and electroplating industries, so that the technologies developed in academia are used by society to achieve not only economic paybacks, but mostly environmental benefits.

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