Case Study for the Development of Heavy Traffic Pavement in Concrete with Bauxite Residue

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Abstract

Developing concretes with bauxite residue (BR) seems to be a good alternative for safe large-scale utilization of this waste. We proved in previous works that it is possible to produce products at a lab scale with a controlled performance in the fresh and hardened state, and some durability aspects similar to ordinary supplementary cementitious materials. However, scaling up from the lab to field is not trivial and sometimes many changes need to be implemented to adapt the process. This was the main purpose of this work. After the development of concretes on a lab scale for the production of paving blocks and monolithic components, a pilot area of approximately 250 m^2 was built using pavement for heavy traffic to monitor performance and durability over time. During the development at small scale, compositions were developed to achieve good flowability and pumpability, characteristic compressive strength higher than 50 MPa for the paving blocks, and flexure strength higher than 4.5 MPa for monolithic production. To scale up, concrete materials were produced at third party concrete plant site for the production of the paving blocks or monolithic material. The paving blocks were produced and kept in storage for a period of 28 days to allow curing of the concrete. A monolithic concrete area was also built on a compacted base and sub-base foundation including steel-bar reinforcement. Results showed that during the production in the field monitoring and adjustments were required during the mixing of concrete to maintain its workability. Careful control of the moisture of all raw materials and dose rate of each were the main challenges. With this control, the production went better than expected as the rheological properties of concretes helped the production of the concrete material. Some opportunities to improve further future production of concrete with BR were also identified.

Keywords: Bauxite residue, Portland cement, Large-scale application, Pavement, Case study.

1. Introduction

The search for applications to reuse bauxite residue is no longer a novelty and the efforts made by universities and industries have been significant. This search has increasingly narrowed the partnerships between Research Centers and Companies that generate the residue.

The main applications evaluated, presently, for BR include synthesis of zeolites, landfill capping, element recovery (like heavy metals, rare earth elements, and other minerals), soil amelioration, production of Portland cement clinker, manufacture of concretes and cementitious components, sub-base and sub-grade for road construction, geopolymers, water treatment, red ceramics, selective filters, and many others [1–14,17–21,24,28,29].

However, the high alkalinity and salinity, the presence of heavy metals, and the great variability of physicochemical and mineralogical properties from site to site are all challenges to the reuse of BR. This is the main reason why less than 4 Mt of the 140 Mt of BR produced annually is utilized [12].

Evans [12], discussing the history, challenges, and new developments in the management and use of bauxite residue concluded that the most successful large-scale uses include applications in cement production, and manufacturing of cement components, like concretes and mortars.

It was also proven in other works that BR has the potential to be used as a supplementary cementitious material (SCM) [15,16,20,22,23,25,27] as it can be a source of Ca, Al, and Si and has a good interaction with the binder. However, it is not yet commonly used in association with Portland cement because some aspects related to leaching and durability need to be better understood.

Another challenge is scaling up from laboratory development to practice in the field: many prototypes and processes developed on a small scale are not viable to be produced on large scale, due to their complexity, embedded costs, or even logistic issues.

In this present work, we carried out a case study to build a concrete (including BR) pavement for heavy vehicle traffic in a truck car park. Two construction techniques were chosen to show the flexibility to achieve the same goal with different concrete solutions: i. construction using paving blocks and, ii. using monolithic concrete. The project was implemented in sequence: the concrete compositions was developed at the lab scale, monitoring and control of the mixing properties was carried out at the concrete plant, production of paving blocks in the field and building the pavement. Finally, a post-installation monitoring of the degradation in use under natural exposure was done and it is planned to monitor the performance for another 2 years.

This strategy was chosen to show that it is possible to scale up the production of cementitious materials using a high amount of bauxite residue and to develop production techniques using existing plant and methods from the civil construction industry.

2. Case Study Area Preparation

The case study aimed to evaluate the use of BR in concrete using two different technologies: (1) jointed plain reinforced pavement, also called monolithic concrete; (2) interlocking concrete block pavement. A section of a parking lot for heavy-duty trucks was renovated, replacing the old floor with pavements using these two solutions.

The chosen area is located in the CBA truck parking lot (23°31'59.6"S 47°15'27.3"W), in the city of Alumínio, state of São Paulo/Brazil. Figure 1 shows how the area was divided between paving blocks (128.2 m²) and jointed plain reinforced pavement (123.6 m²). In this last application, five slabs (M1 to M5) of about 25 m² each, were built. The prepared area, with steel mesh reinforcement and joints with load transfer steel bars (dowels), is illustrated in Figure 2.

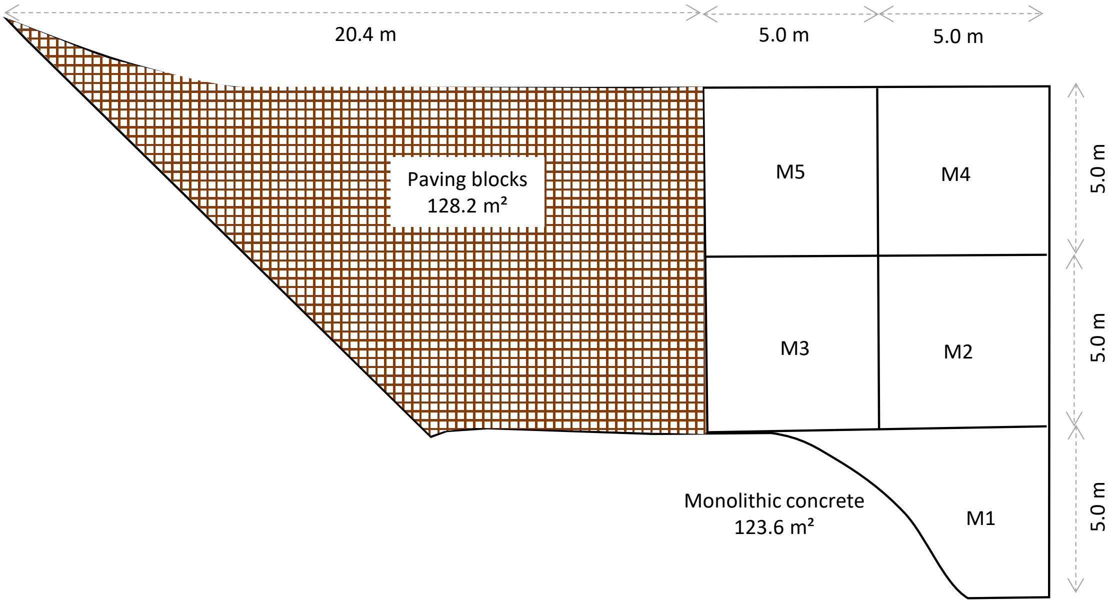

Figure 1. Sketch of the area for the pavement construction in the CBA truck parking lot.

Figure 2. Preparation of the jointed plain reinforced pavement: side formwork and steel reinforcement (left); concrete mixing truck, concrete pump, and pipeline used to conduct the concrete from the pump to the placing site (right).

3. Materials and Development of Concretes

The work started with the laboratory development of the concrete to be used. The chosen recipe was approved by the concrete company that later carried out the production and placement of the concrete. Several compositions were formulated changing the amount of cement and bauxite residue, the water content, type and quantity of chemical additives and the ratio between coarse aggregates and mortar.

The choice of the materials used in the formulations was based on performance criteria related to the presence of BR, the availability of materials to the concrete company, and the technical characteristics of execution and specified performance.

The target for the composition to be applied as a monolithic concrete was minimum flexural tensile strength of 4.5 MPa after 28 days of cure, modulus of elasticity > 30 GPa, water-to-cement ratio $\leq$ 0,50 (due to the specified aggressive environmental class). The concrete should be pumpable, with a slump of 120 ± 20 mm, and maintain workability for at least 2 hours.

A CPII-E 40 type Brazilian Portland cement, blended with up to 34% ground blast furnace slag, was chosen, because it was proved in previous works of our group that this is the binder with the better chemical interaction with BR, mainly in terms of the alkalis fixation after hardening [23,24]. For that, it was also used silica fume to promote pozzolanic reaction with calcium.

The concrete for the paving block production should have a compressive strength of 50 MPa after curing period of 28 days, a slump flow of 500 ± 20 mm, and maintain workability for at least 4 hours.

Table 1 shows the final compositions developed in the lab and used later in the field production. The ratio between BR and Portland cement for paving blocks was 15%-vol/vol, and for the monolithic concrete was 20%-vol/vol. These percentages can be considered as significant amounts of bauxite residue for use in cement compositions.

Table 1. Concrete compositions for paving blocks and monolithic paving slabs

Raw material	**PAVING BLOCKS (kg/m³)**	**MONOLITHIC (kg/m³)**
Cement	424	350
Silica fume	20	20
Bauxite residue	65	75
Natural sand	291	229
Manufactured sand	435	425
Aggregate 0 (<9.5 mm)	894	274
Aggregate 1 (<19 mm)	-	824
Polyfunctional additive (Maximent PXT84)¹	2,20	2,96
Superplasticizer (Maxifluid H3055)²	-	2,22
Superplasticizer (Maxifluid H3090X)²	5,33	-
Hydration stabilizer²	1,78	-
Water²	209	185

Concrete for paving blocks was produced only with aggregate with a maximum size of 9.5 mm mainly due to the thickness of each piece (8 cm), while the ‘monolithic’ concrete was formulated with aggregates up to 19 mm.

Polyfunctional and superplasticizer additives were used in both recipes, but, as for the paving blocks a larger flowability was needed, a more efficient product, and in a large amount, was used. This superplasticizer, associated with the hydration stabilizer, helped with the workability time during the production of the pieces in the field.

4. Production in the Field

All concrete was produced in a concrete batching plant in São Roque city (23°32'06.8"S 47°09'14.9"W), 15 km distant from the CBA truck parking lot, as per the formulations described in Table 1.

The mixing sequence was the same, independently of the kind of application:

i. The coarse aggregates and sands were inserted into the concrete mixer by a conveyor belt.
    - Bauxite residue and silica fume were also added to this belt, on top of the aggregates, at the start of loading.

ii. Cement was added from the silo at the same time as water + polyfunctional admixture. From the total water, the moisture content of the coarse aggregates, sands, and BR was discounted.
iii. Homogenization was performed for 5 minutes.
iv. Addition of 75% of the expected superplasticizer.
    - for the concrete used to produce paving blocks, the stabilizer agent was also added.
v. Homogenization for 5 minutes.

After this procedure, about 30 liters of concrete were collected for the slump (and flow) evaluation. If the fresh property was not considered adequate, the flowability of concrete was adjusted by adding more superplasticizer. Only after adequate workability was obtained, delivery was authorized. Part of this process is illustrated in Figure 3.

Figure 3. Illustration of the stages of addition of bauxite residue, silica fume, and superplasticizer into the concrete. Below, it is shown the moment when a portion of concrete is collected from the truck for fresh state evaluation.

The transit time between the concrete plant and the construction area was around 30-60 minutes. When the truck arrived, another control of the fresh state was performed. If some intervention was necessary, the slump, or flow, was achieved by adding more superplasticizer. We did not want to add any more water.

4.1 Construction with Monolithic Concrete

After the arrival of the first truck on site, the fresh state of the concrete delivered for the production of the monolithic floor was evaluated again. Once the slump test was approved, the truck was positioned in front of the pump to transport the concrete by pumping to the chose area.

One person was responsible for pipeline control and pouring the concrete into the prepared area, while the others were responsible for spreading, vibrating, leveling, and finishing the surface, as shown in Figure 4.

The area was built with 5 trucks delivered to the site in sequence. At the end of the day, a wet cover was placed over the pavement (cover was kept wet at all times) to ensure the wet curing of the concrete.

While the area was filled with concrete, some samples (cylinders for compressive strength and prisms for flexural strength) were molded for hardened state evaluation (Figure 5). It was necessary to verify the parameters after mixing at the concrete plant to evaluate the repeatability of the concrete production process with BR for each batch to compare with the results obtained previously in the laboratory.

Figure 4. Stages during the production of the pavement using monolithic concrete.

Figure 5. Preparation of samples for the hardened state control of monolithic concrete.

After 28 days of curing, we tested the samples prepared with the concretes collected in the first 4 trucks, and measured the flexural tensile strength presented in Table 2, showing that the target of the mechanical property (4.5 MPa) was achieved. Batch 4 presented the lowest strength because we had a problem with the water control during the mixing, having added too much water than defined in the project.

Table 2. Flexural tensile strength after curing for 28 days.

Curing for	Batch 1	Batch 2	Batch 3	Batch 4	Average
28 days	6.57 ± 0.21	6.14 ± 0.05	6.62 ± 0.39	5.67 ± 0.11	6.25

4.2 Paving Blocks

To enable good productivity, it was decided to build a molding bench to place the molds, and shelves to store them after casting for initial curing. The molds were placed side by side on the bench and the concrete was poured over them, directly from the truck, as illustrated in Figure 6, as it presented self-leveling characteristics. The upper surface was leveled and the concrete spread evenly throughout the molds using a masonry trowel.

The molds were, then, placed on shelves. Buckets with water were placed on the floor and the shelves were covered with plastic canvas to ensure humidity inside. The paving blocks were removed from the mold after 1 day of curing and stored sheltered from natural weathering until the moment of use on the site.

Due to the number of molds acquired, the production of the pieces was done in 5 batches of 3 m³ of concrete, delivered in a single truck. On average, each batch took about 1 hour to be finished, producing around 600 pavers.

The paving blocks were cured for 28 days and then used to construct the pavement. Part of the pieces was kept stored without contact with humidity, being used as control references for the evaluation of the properties of the exposed floors under natural using conditions (heavy vehicle traffic, rain, wind, sun, etc.).

Figure 6. Production of paving blocks.

While the paving blocks were being produced, some cylindrical specimens were molded for compressive strength. As in the production of monolithic concretes, here we also seek to verify the parameters obtained after mixing in the concrete plant and thus evaluate the repeatability of the concrete production process with BR, as well as to compare with the results obtained previously in the laboratory scale. Results after 7 and 28 of curing are presented in Table 3. It was clear that our target (> 50 MPa) was achieved.

Table 3. Paving blocks compressive strength after 7 and 28 days of curing.

Curing for	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Average
7 days	54.1	49.9	52.1	56.9	50.8	52.8
28 days	67.9	61.8	65.1	69.4	63.8	65.6

5. Post Installation Evaluation

The new pavement was free from traffic for only 15 days after the work was completed. From then on, the evaluation from abrasion caused by the action of trucks and weather had started. Part of the test area is illustrated in Figure 7.

The purpose of this work was to build and monitor the performance and durability of applied paving blocks for at least two years. At the moment of writing this paper, the pavement has been exposed to traffic and weather for a period of only 6 months so far.

As part of the performance testing, some paving blocks were removed and sent evaluations. New (unexposed) pieces replaced the removed ones. These new paving blocks were properly identified and will not be removed for further evaluation over time. To compare the impact of natural versus in-use exposure, some pieces that were kept away from traffic and environment exposure were also evaluated.

Figure 7. Pavement with paving blocks and with monolithic concrete.

After removal, each block was cleaned with a dry brush and packed in a plastic bag to avoid additional contact with water and sent for evaluation:

i. Dimensional variation, compressive strength, water absorption, and abrasion resistance: following the Brazilian Standard NBR 9781/13 – Concrete paving units – Specification and test methods.

ii. Leaching: according to the NBR 10005/04 – Procedure for determine leaching extract from solid waste. The paving blocks were crushed and passed through a 9.5 mm sieve. A representative sample of 100 g was transferred to the leaching bottle, and an extraction solution was added (maintaining a ratio of 1:20 in mass). pH measurement of the concrete sample in deionized water and HCl solution was carried out as per the procedure (pH higher than 5), which indicated an extraction solution with 5.7 mL of glacial acetic acid + deionized water (to complete a volume of 1 L). The sample in the leaching bottle was stirred for 18 ± 2 hours on a rotary shaker and then vacuum filtered with a resin-free glass fiber filter with a porosity of 0.6 to 0.8 µm. The leachate extracts were sent for heavy metals concentration analyses (*silver, arsenic, barium, cadmium, chromium, lead, selenium, and mercury*) using inductively coupled plasma atomic emission spectrometry and cold vapor atomic absorption for mercury quantification. The fluoride concentration was also analyzed using the selective ion method.

iii. Solubility: according to the NBR 10006/04 – Procedure to determine solubilized extract of solid waste. The same protocol of grinding and sieving described previously was applied, and a sample of 250 g was transferred to the solubilization flask, adding 1000 ml of deionized water (organic-free water). After manual stirring at low speed for 5 minutes, the mixture was kept covered and left to stand for 7 days. After this period the solution was vacuum filtered through a 0.45 µm pore size filter. The solubilized extract was sent for analyses to determine concentration of the following constituents: *Silver, Aluminum, Arsenic, Barium, Cadmium, Chromium, Copper, Iron, Potassium, Manganese, Sodium, Lead, Selenium, Zinc, Mercury, Sulfates, Nitrates, Chlorides, Fluorides, Cyanides, and Phenols*. The methods employed were ion selective detection and atomic absorption spectrometry. The pH was also determined.

Table 4 shows the results obtained for this first monitoring, for both exposed and unexposed (Ref) paving blocks. The tests on the paving blocks were only carried out on batches 2 and 4. We choose these two batches based on the mechanical strength results, measured after 28 days in cylinder samples. The overall average was 65.6 MPa, but batches 2 and 4 presented the lowest and highest strength respectively (see Table 3). Independently of that, every batch achieved strength higher than 50 MPa, suitable for heavy traffic.

Table 4. Summary of the results (average and standard deviation) obtained during the monitoring of the hardened state of paving blocks. The limits represent the values for each parameter for heavy traffic, according to the Brazilian standard NBR 9781.

Parameter	**Batch 2 ref**	**Batch 2 exposed**	**Batch 4 ref**	**Batch 4 exposed**	***Specimens evaluated***	***Limits***
Thickness (mm)	77.1 ± 4.4	79.9 ± 0.9	82.0 ± 1.8	81.6 ± 2.3	*6*	*80* ± 3
Specimens outside the limit [1]	*2*	*3*	*3*	*3*	-	-
Water absorption (%)	2.5 ± 0.31	2.6 ± 0.21	2.4 ± 0.14	2.1 ± 0.09	*3*	*5.0*
Compressive strength (MPa)	71.4 ± 2.29	74.4 ± 2.26	66.5 ± 0.90	72.9 ± 1.92	*6*	*50.0*
Abrasion resistance (mm)	16.5 ± 0.55	17.2 ± 1.48	17.8 ± 0.49	16.7 ± 0.66	*3*	*20.0*

[1] number of specimens that presented thickness lower than 77 mm or higher than 83 mm.

The main purpose of this work was to verify the degradation of the components due to exposure and use as well as evaluating the challenges of scaling-up the production of concrete with bauxite waste. For that, the exposed and unexposed blocks of the same lot were compared.

The evaluation of the thickness of the paving blocks provided some idea of the control during the manufacturing of the pieces. The values obtained, on average, are within the specification indicated in the Brazilian technical standard. However, as can be seen in Figure 8, the leveling of several pieces was not properly performed. The molding strategy proposed for this case study was designed to facilitate production in the field, but the finishing was not performed as desired. Thus, for future productions, more stringent control will be needed for this production stage.

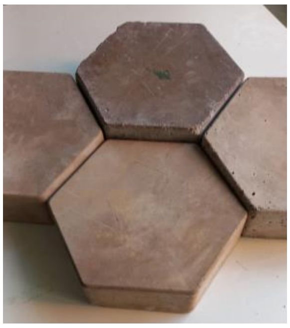

Figure 8. Comparison of the thicknesses of some paving blocks removed for evaluation.

The other measured properties meet the normative specifications for paving blocks used in heavy vehicle traffic areas. Additionally, no trends were observed as a function of exposure or not of the paving blocks. Therefore, considering these analyzed properties, no deterioration was observed due to exposure in the first 6 months of use.

In addition to the mechanical characteristics, the release of soluble ions from the components in use, which is potentially dangerous to the surroundings of the construction site, was evaluated through leaching and solubilization tests. Results are presented in Tables 5 and 6, respectively for leaching and solubilization of elements.

The leaching test employed in this study is used to classify wastes as hazardous or not according to the specification of Brazilian standard NBR 10004 – Solid waste – Classification. The leaching and solubilization evaluation aim to assess the paving blocks from the point of view of their final destination, after the end of their useful life.

It is important to emphasize that the objective of this standard is to classify solid waste, i.e., materials that result at the end of a production process, or that have no useful destination and are landfilled.

In the case of paving blocks made from concrete with BR, this situation will occur at the end of the useful life, when they will be demolished, possibly crushed, and then deposited in some landfill. In this final condition, reduced to small particles, if the disposal is inadequate, it will be exposed to leaching of its components and may pose a risk to public health and the environment, if these components are hazardous.

Table 5. Leached constituents of paving blocks.

Element	Batch 2 ref	Batch 2 exposed	Batch 4 ref	Batch 4 exposed	Limit of detection (mg/L)	Limit of NBR 10004 (mg/L)
Silver (Ag)	ND	ND	ND	ND	0.025	5.0
Arsenic (As)	ND	ND	ND	ND	0.025	1.0
Barium (Ba)	0.32	0.37	0.20	0.42	0.010	70
Cadmium (Cd)	ND	ND	ND	ND	0.003	0.5
Chromium (Cr)	ND	ND	ND	ND	0.010	5.0
Lead (Pb)	ND	ND	ND	ND	0.010	1.0
Selenium (Se)	ND	ND	ND	ND	0.025	1.0
Mercury (Hg)	ND	ND	ND	ND	0.0008	0.1
Fluoride (F^-)	3.02	3.44	3.88	2.76	0.60	150

ND – not detected

Leaching (using acid digestion method) of heavy metals such as silver, arsenic, cadmium, chromium, copper, and manganese was not detected. If these elements were present in the paving blocks, they were chemically fixed or the amount so low that it is not possible to detect.

Barium and fluoride results are very low and well below the Brazilian standard specification. There is no correlation with the exposure in use: the observed variations are probably due essentially to the variability of composition and sampling. In summary, the heavy metals evaluated would not be an environmental problem for the use of this product on the pavements.

Based on this evaluation, a residue from these paving blocks would not be classified as hazardous but would be potentially non-hazardous (Class II): no evaluated elements were detected in a concentration higher than specified.

The second assessment aims to sub-classify the produced paving blocks as reactive (Class II-A) or non-reactive (Class II-B) products.

For that purpose, we used the solubilization test, carried out in deionized water. This sub-classification aims to assess whether the waste deposited in the natural environment releases constituents that can potentially contaminate soil or water resources.

The alkalinity of the concretes with bauxite residue was similar to that observed for conventional concretes with results between 12.52 and 12.73 regardless of exposure condition.

Table 6. Solubilized constituents of paving blocks.

Element	**Batch 2 ref**	**Batch 2 exposed**	**Batch 4 ref**	**Batch 4 exposed**	**Limit of detection (mg/L)**	**Limit of NBR 10004 (mg/L)**
Silver (Ag)	ND	ND	ND	ND	0.025	0.05
Aluminum (Al)	0.85	1.06	2.51	1.98	0.010	**0.20**
Arsenic (As)	ND	ND	ND	ND	0.008	0.01
Barium (Ba)	0.12	0.12	0.08	0.08	0.010	0.70
Cadmium (Cd)	ND	ND	ND	ND	0.003	0.005
Chromium (Cr)	ND	ND	ND	ND	0.010	0.05
Copper (Cu)	ND	ND	ND	ND	0.010	2.0
Iron (Fe)	0.05	0.05	0.07	0.09	0.010	0.30
Manganese (Mn)	ND	ND	ND	ND	0.005	0.10
Sodium (Na)	290.1	262.6	281.4	294.6	0.060	**200.0**
Potassium (K)	225.6	192.8	190.0	180.0	-	-
Lead (Pb)	ND	ND	ND	ND	0.007	0.01
Selenium (Se)	ND	ND	ND	ND	0.008	0.01
Zinc (Zn)	0.004	ND	ND	ND	0.003	5.0
Mercury (Hg)	ND	ND	ND	ND	0.0008	0.0001
Sulfates (SO_4^{-2})	10.9	8.03	10.5	12.6	4.0	250.0
Nitrates (N)	1.37	1.42	1.47	1.27	1.5	10.0
Chlorides (Cl^-)	11.7	11.0	10.5	10.7	0.50	250.0
Fluorides (F^-)	0.60	0.57	0.71	0.76	0.60	1.5
Cyanides (CN^-)	ND	ND	ND	ND	0.05	0.07
Phenol	ND	ND	ND	ND	0.005	0.01
pH	12.73	12.53	12.52	12.62	-	-

ND – not detected

Most of the elements specified in the Brazilian standard for solubility assessment were not detected from deionized water extraction (silver, arsenic, cadmium, chromium, copper, manganese, lead, selenium, mercury, cyanides, and phenols), while some the elements have results below the safe limit for application (barium, iron, zinc, nitrates, chlorides, and fluorides).

Potassium was solubilized in large amount, but as there is no limitation in the standard, it was not considered a problem for the development of these products. The amounts of aluminum and sodium were high and above the specified limits. However, aluminum and sodium solubility do not appear to be related to exposure. In some cases, there is even a content increase in the exposed elements. So far, there is no evidence to demonstrate that there is solubilization of these two elements to the environment.

So, if we consider the final destination of these paving blocks (at the end of service life or as a waste resulting from the construction), we would have to classify the waste as Class II-A (not dangerous, but reactive). It is worth noting that this is not uncommon for construction waste.

Strategies could be developed if needed to reduce concentrations of these elements in the leachate such as using supplementary cementitious materials: increase the pozzolans and slags content or use Portland cement with a high amount of slag [24–26]. Reducing the amount of BR or optimizing the ratio between BR and Portland cement can also be considered.

If we consider that the current form of exposure did not affect the leaching, these elements will not contaminate the site where the paving blocks are being used. This is very useful information because we can infer that these kinds of concrete can be applied in places without exposure to environmental conditions.

6. Conclusions

The case study presented in this paper aimed at demonstrating the potential of scaling up the production of concretes with bauxite residue generated from the Bayer process.

A section of pavement for heavy vehicles traffic was built applying two different construction techniques: paving blocks and concrete monolithic slabs. Choosing more than one option seeks to show the flexibility of application of this kind of product and is an indication that the techniques could be applied to produce other kinds of components used in civil engineering.

The conclusions from this case study are as follows:

- it is possible to scale up the production of concretes with bauxite residue: concretes were developed with good flowability, pumpability, and adequate workability time.
- some adjustments were needed during the production in the concrete plant and the control of fresh property using the slump test allowed us to deliver concretes with adequate properties.
- building the pavement with monolithic concrete was easier during concrete pouring after preparing the area with steel reinforcement on site;
- the production of paving blocks in the field was easy and quick with around 600 pieces per hour.
- the paving blocks and monolithic concrete applied in the field presented properties equivalent to those developed in the lab-scale;
- the products exposed for 6 months to traffic and weather did not present deterioration in terms of compressive strength, water absorption, and resistance to abrasion. These properties were similar between the exposed elements and reference elements kept unexposed throughout this period.
- leaching of heavy metals was not detected (or detected well below the limits established by Brazilian standards);
- Na and Al were the only elements higher than established by Brazilian standards. So far, there is no evidence to demonstrate that there is solubilization of these two elements to the environment.
- Finally, to produce a safer solution in the future development, it is recommended to adjust the mix design and choose materials that are more suitable for fixation of the soluble Na and Al coming from the use of BR.

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