Case Study of a Potential Large-Scale Application for Bauxite Residue in the Composition of Paver Blocks: Evaluations of Producing, Building and Monitoring Performance and Durability

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Abstract

The roadmap of the International Aluminium Institute pointed out that one of the most impactful applications for bauxite residue (BR) is in association with Portland cement, during the production of clinker or as a supplementary cementitious material in mortars or concretes. In our previous research, we showed, on a laboratory scale, that it is possible to produce different kinds of cement products and components with BR, like rendering mortar, urban furniture, hydraulic tiles, or concrete for general application. The pursued strategy was to apply BR while reducing the environmental impact (reducing Portland cement content, using a safe but high percentage of BR, producing components with low environmental risks etc.), and cost (no intermediary process or treatment of residues were necessary, like calcination or other thermal treatments). However, scaling-up production may introduce new difficulties, representing a significant challenge. This work was performed with the main purpose of building an area for light traffic with concrete paver blocks produced with Portland cement and bauxite residue. So far, the research has gone through the stages of the concrete composition development (two compositions with BR and one reference concrete), component production in the field in the order of several thousand pieces, preparation of area and installation of the paver blocks, and monitoring of performance of the applied products. Mechanical properties, abrasion resistance and water absorption were some of the properties evaluated over the first year after production. Results allow us to understand the challenges to produce concretes using a waste with many restrictions, the impact on the global CO_2 released, the classification of compositions according to environmental standards, and others. The performance and durability evaluation for one year of the developed components indicate a safe potential large-scale application for BR, but the monitoring continues to be performed for longer periods.

Keywords: Bauxite residue, Portland cement, paver blocks, field application, performance, resistance to abrasion.

1. Introduction

As the world population continues to grow, there is a need to increase and improve the urban infrastructure and the number of houses[1]. Thus, the use of cementitious materials such as concrete and mortar tends to increase worldwide [1,2]. By keeping the current composition dosage strategies and construction practices, an increase in environmental impact is expected. High

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[1] www.unhabitat.org

amounts of Portland Cements are currently produced worldwide to feed this production chain, releasing a considerable volume of CO_2 into the atmosphere [2–5].

Therefore, the need to reduce cement consumption has grown, mainly in scientific research. As a replacement, supplementary cementitious materials, reactive or not, has been increasingly sought and studied, but some of them have limited reserves, requiring a continued search for other options [3,4,6–10].

In parallel, the search for large-scale applications for bauxite residue (BR) has been intensified in recent years and the association with Portland cement in such compositions has been shown to be one of the most promising options [11–21].

The presence of aluminium, silicon and iron in high amounts can help in the chemical interaction between BR and cement during the formation of hydrated compounds [12,17,22–24]. However, an observed problem is that BR shows considerable chemical, mineralogical and physical variations between production sites, and a suitable solution for a collected sample may not be adequate for another one [25,26]. A monitoring study carried out by Garcia [27] indicated that the iron content can range from 20 to 60%, aluminium from 10 to 58%, silica from 3 to 65%, and sodium from 0.4 to 15%, reflecting considerable chemical and mineralogical variability.

Furthermore, the cement-BR interaction depends on the type of Portland cement used and its properties. It is not possible to simply develop a mixture without specific technical criteria and evaluations consistent with the type of components and their production process [22]. So, this is a complicating factor for the implementation of this application [13].

In some research, both in literature and websites, extremely high BR levels can be used in cementitious compositions, sometimes exceeding 20% of the concrete volume [11,15–18,20, 24,25,28–30], replacing cement or sand. However, although components were produced with good appearance and some properties suitable for application in different sectors, it was not possible to guarantee that the environmental aspects were safe, mainly due to the lack of control of the chemical fixation of soluble alkalis or due to durability issues, i.e., leaching, efflorescence, alkali-silica reaction, steel bar corrosion and others.

Thus, despite the search for large-scale applications for BR and the reduction in cement consumption being global needs, the interaction between them must be done in a safe and responsible way.

In addition, the proposed solutions must also consider logistical issues, seeking to be adapted to the local market, reducing the need to transport raw materials over long distances, production in regions close to the BR generating plants and consumer markets.

An application with the potential for large-scale use of BR is the production of urban infrastructure components, such as paving blocks. The production of compositions can be made in concrete batching plants and sent to be molded in loco; or a production plant can be built inside or close to the BR generating plant, greatly reducing the need for transportation.

In this sense, this work was carried out with the objective of producing paving blocks and building a test area for light vehicle traffic within Alunorte's plant facilities, to monitor the degradation of the product and the environmental aspects related to leaching of soluble ions into the environment over several years.

2. Experimental

2.1 Materials

Concretes were formulated with Portland cement, named as CPIIF (produced according to the Brazilian standard with up to 75–89% of clinker + source of sulphates, and 11 to 25% of limestone filler), silica fume, sand, crushed stone coarse aggregate, bauxite residue (BR) from Alunorte, and chemical admixtures to promote water reduction and cement hydration reaction stabilization.

2.2 Compositions

Three concretes, as shown in Table 1, were formulated. A reference composition (Conc1) was prepared without bauxite residue based on which two concretes with BR were proposed: Conc2, where part of the sand was replaced by the same volume of BR; and Conc3, where part of the Portland cement was replaced by the same volume of BR. In both cases, the relation of BR/cement was kept constant and equal to 15%. In Conc3, the lower cement content aimed to evaluate the possibility of using BR as an option to reduce environmental impact by reducing CO_2 emissions generated in cement production. Water-to-cement ratios were kept constant at 0.44 for all compositions.

Table 1. Mix design of the concretes, in kg/m³.

Raw material	Conc1 (REF)	Conc2 (BR/S)	Conc3 (BR/PC)
Portland cement - CPIIF40	435	435	405
Silica fume	30	30	28
Sand	725	668	725
Crushed stone	975	975	975
Bauxite residue	-	65	60
Maximent PXT76	3.53	3.53	3.53
Maxifluid 1120	3.61	3.61	4.51
Hydration stabilizer	1.86	1.86	1.86
Water	190	190	180

In the first stage of this project the compositions were evaluated on a laboratory scale to monitor workability, moldability, open time and mechanical strength. For good production conditions a flow of 460 ± 20 mm was established, and all the concretes were produced in laboratory with a compressive strength of 70 ± 2 MPa at 28 days.

2.3 Production of paving blocks

After the laboratory-scale development, the *in loco* pilot-scale production was performed. For each batch of 3m³ of concrete, around 450-500 pieces of paving blocks were produced. The concrete was mixed in a commercial batching plant and delivered to the site where the blocks were produced. Then, the BR and superplasticizer were added, finishing the mixture. The workability control was done by measuring the flow and once approved, production was started. Figure 1 shows some pictures that illustrate the stages of production of paving blocks.

After finishing the production, the pieces were cured for at least 28 days and covered with polyethylene plastic film to avoid contact with the external environment.

Figure 1. Concrete paver block production process: 1. molding bases, concrete transport buckets, and plastic molds; 2. Organization of the space to start the production; 3. Applying release agent; 4. Concrete mixer truck arrival (without BR addition); 5. BR weighing; 6. BR addition; 7. Concrete with BR; 8. Flow test; 9. Molds prepared to receive the concrete; 10. Molding and surface finishing; 11. Storage of pavers for curing; 12. First blocks produced after 24 hours.

2.4 Construction of the test area

To build the traffic area, a place inside Alunorte's refinery site of around 400 m^2 (Figure 2), was chosen. Inside this area, the paving blocks produced with the three different concrete compositions were divided into three areas. A part of the produced blocks was stored without environmental contact near to the built floor. These unexposed blocks were used as a reference for time of cure, to compare with the exposed blocks and to replace the exposed blocks that were removed for evaluation.

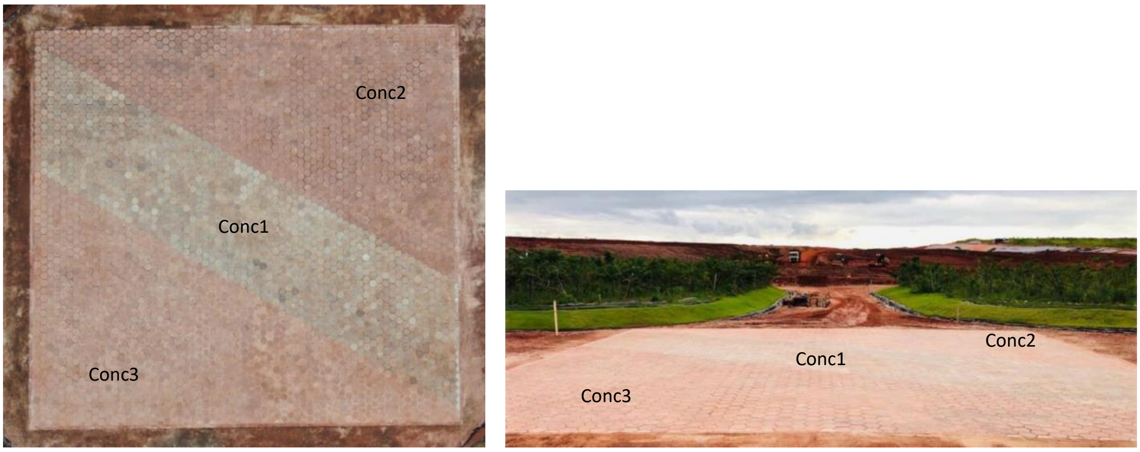

Figure 2. Illustration of the built floor, indicating the compositions used at each area.

Each block was identified using an alpha-numeric system, illustrated in Figure 3. In the picture shown in the left, column C (yellow arrow) and row 1 (arrow and hatch in blue) are highlighted, as an example of how the pieces were identified. The picture on the right shows the last column (BM, on the other side of the area) and the finishing with half a piece, exactly as shown in the layout design.

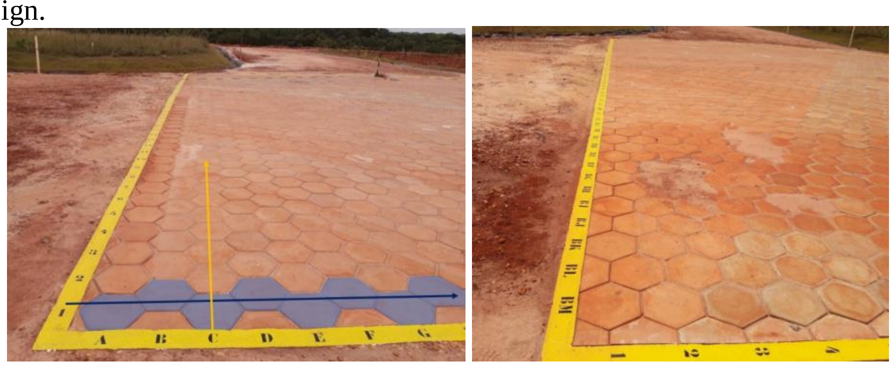

Figure 3. Exemplification of the numbering of each piece in the area

2.5 Sampling plan for removing paving blocks for evaluation

After construction, some blocks were removed after 100, 200, and 355 days of the exposure to the natural weather of Barcarena (state of Pará, northern Brazil). Figure 4 shows the sampling map obtained after the aleatory piece for each composition was taken after 200 days of exposure. After each removal, an unexposed block was replaced in the vacant locations and these blocks were not considered for future samplings.

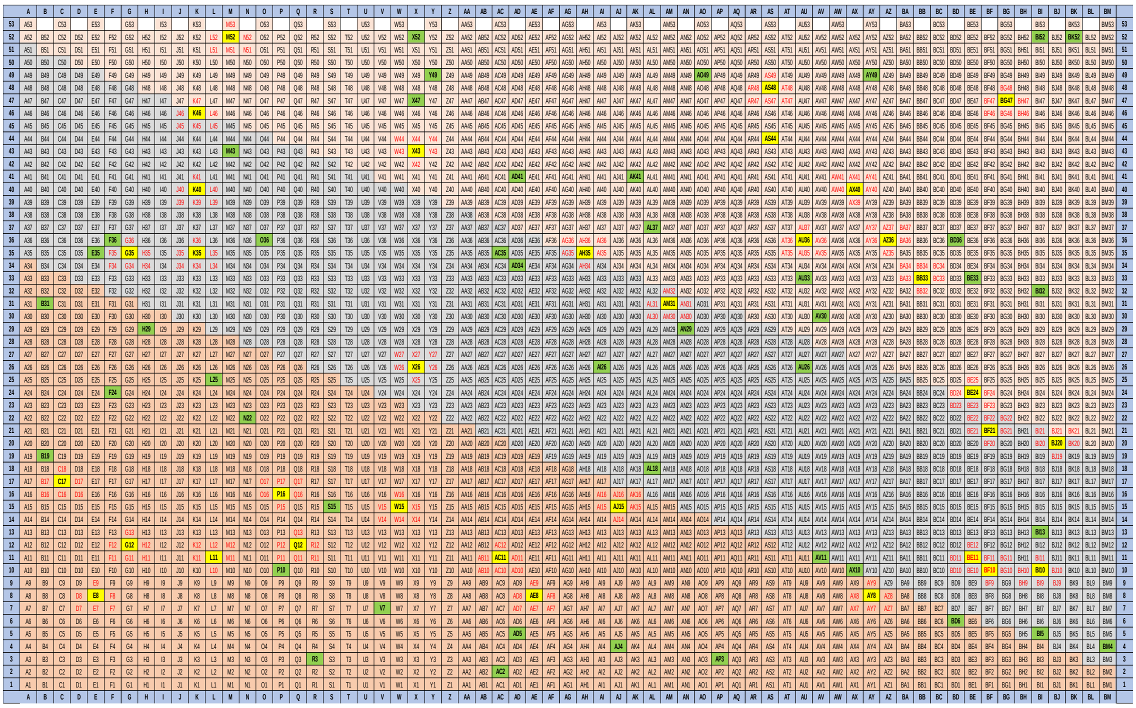

Figure 4. Map illustrating the sampling of pieces removed after 100 (yellow) and 200 (green) days of exposure.

After extraction, each block was cleaned with a dry brush and packed in a plastic bag to avoid additional contact with water and then sent for evaluation as described below.

2.6 Methods of testing

First a visual evaluation was performed, looking for problems of molding or degradation due to the exposure on the site. Cracking, efflorescence, surface micro defects were some of the problems evaluated. This was not a selection criterion, but a way for a qualitative evaluation of each collected piece.

Next, the blocks were evaluated following the recommendations of the Brazilian Standard (NBR) described in Table 2**Table** . The number of pieces used in each test is also indicated.

Table 2. Tests used to evaluate the blocks

Test	Brazilian Standard	Number of pieces for each composition and time of exposure
Dimensional variation	NBR 9781 (2013)	6
Compressive strength	NBR 9781 (2013)	6
Water absorption	NBR 9781 (2013)	3
Resistance to abrasion	NBR 9781 (2013)	3

The basic requirements for concrete paving blocks were evaluated, according to ABNT NBR 9781 (2013). To determine the alkali content, chemical analysis was performed by the methods described in ABNT NBR NM 22 (2012), applied specifically for the evaluation of cements with pozzolan addition.

3. Results and Discussion

The visual evaluation indicated that none of the blocks had cracks, efflorescence or macro defects on the surface that could affect the performance in use. Table 3 represents a summary of the dimensional quantification of the collected paving blocks.

Table 3. Dimensional variation of paving blocks
Nominal width = 300 mm, Nominal height = 80 mm

Time of exposure (days)	Composition	Width (mm)	Height (mm)
0	Conc1	296	84
0	Conc2	296	83
0	Conc3	296	82
100	*Conc1*	*297*	*84*
100	*Conc2*	*297*	*81*
100	*Conc3*	*297*	*81*
0	Conc1	298	82
0	Conc2	299	81
0	Conc3	298	82
200	*Conc1*	*299*	*82*
200	*Conc2*	*298*	*81*
200	*Conc3*	*298*	*82*

It is possible to conclude that the width had a negligible variation and was not influenced by the concrete composition or curing time. The global mean width was 297 ± 2 mm: despite the nominal dimension of 300 mm, the plastic mold has a slight inclination along the height, to allow the removal of the piece from the mold. Monitoring the height illustrates a global mean of 82 ± 2 mm, slightly larger than the nominal value of 80 mm. This was obtained due to some inconsistency during the filling of the forms by the masons, but this was not considered a problem because it is within the allowed limits of the Brazilian Standard.

Figure 5 summarize the compressive strength. All the batches had a characteristic strength greater than 50 MPa, which according to the Brazilian standard is suitable for traffic of special vehicle and demands capable of producing abrasion effects.

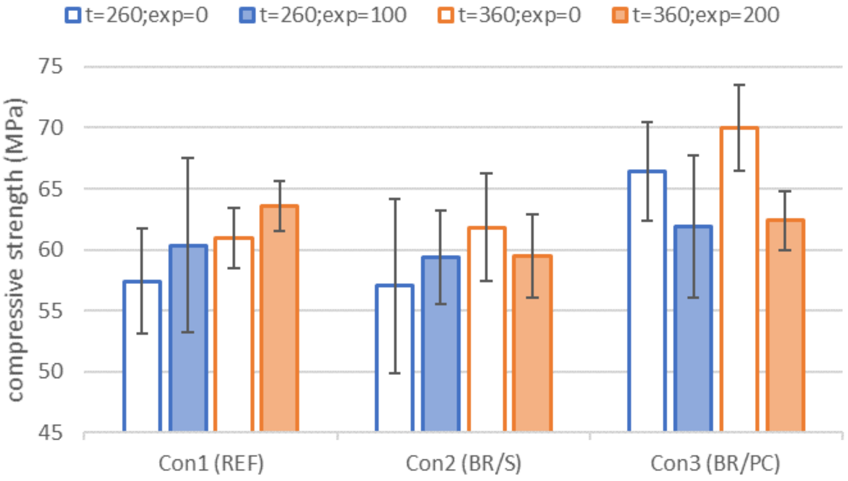

Figure 5. Compressive strength of paving blocks after 0, 100 and 200 days of exposure. The legend label "t" refers to curing age and "exp" refers to exposure time, both in days. The error bar represents the 95% confidence interval of 95%.

Assessing the standard deviation, there are values ranging from 2.2 to 7.3 MPa, representing a considerable amplitude. This variation comes from the variability between production batches and within batches, possibly as a result of:

- variability of the primary composition, which was produced in the concrete plant and send to the block production place.
- variability during the introduction of BR and adjustment for consistency in the field.
- loss of workability during production time, leading to difficulty in molding.

Although concrete plants tend to optimize production over time to reduce the variability, some issues were observed during the production of these floors that could be attributed to deviations in the concrete plant.

Additionally, the workability adjustments were carried out only with superplasticizer, which has little effect on the porosity of the concrete. Moreover, as the production time in some cases was long, adjustments were required multiple times to guarantee the recommended flow of molding. Production of blocks with variable flowability can promote surface defects which can affect the performance of the product.

There may also be blocks that suffered some damage due to vehicular traffic. This effect, however, can be considered as small because there is no evidence of a reduction in mean strength or an increase in standard deviation comparing the exposed and unexposed blocks.

Independent of that, Conc2, in which bauxite residue (BR) was introduced replacing sand, presented compressive strength equivalent to the reference concrete. In Conc3, in which BR replaced partially the Portland cement, there was a slight reduction in water consumption to compensate for the reduction in binder content, resulting in an increase in strength of around 9

MPa in the non-exposed parts. This difference is significant, indicating that there is potential to obtain improvements in performance with adjustments in the formulations, being able to insert BR, reduce cement consumption and still obtain an improvement in mechanical strength.

Comparing Conc1 and Conc2 (compositions with similar cement content), the introduction of BR may not have provided an increase in strength, but it certainly did not reduce it.

Results of abrasion wear are shown in Figure 6. Individual values were between 20.0 and 22.8 mm. In general, abrasion variability was small (except for 1 sample from Conc2 at 100 days). In this interval, according to NBR 9781 (ABNT, 2013), all specimens were classified in the same class: pedestrian traffic, light vehicles, and commercial vehicles. They would, for example, be suitable for sidewalks, squares, light vehicle parking and secondary urban roads. To suit the heavy traffic class, which refers to special vehicles and demands capable of producing accentuated abrasion effects, the wear determined by this test must be at most 20 mm.

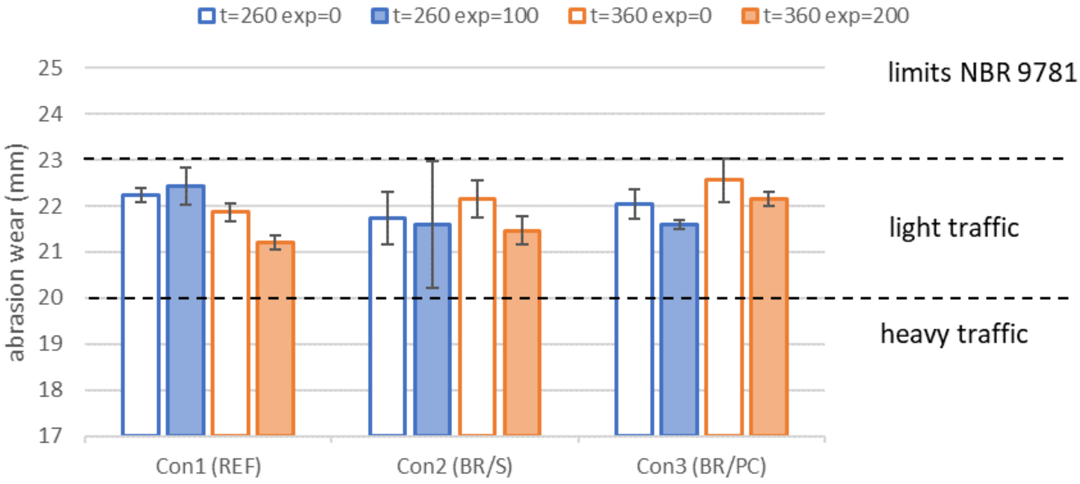

Figure 6. Abrasion wear of paving blocks after 0, 100 and 200 days of exposure. The legend label "t" refers to curing age and "exp" refers to exposure time, both in days. The error bar represents the standard deviation.

There were no significant changes in the abrasion wear due to the compositions and time of cure/exposure. So, in this case, the use of BR did not affect this property.

It is noteworthy that the compressive strength obtained allows for the use of these blocks in heavy traffic areas. In this way, the paving blocks would not be structurally damaged if they were subjected to heavy traffic. Abrasion wear would not be expected if a vehicle with a higher load passed over these floors since the abrasion process is continuous in nature. It is still necessary to emphasize that according to Brazilian standards, the abrasion evaluation is an optional test. Despite these considerations, it is recommended that this property should not be neglected, so that a satisfactory performance can be guaranteed throughout the life cycle of the pavement.

The results of water absorption are shown in Figure 7, illustrating a small variability for all compositions, and that all batches met the limit specified by the NBR 9781 (≤6%).

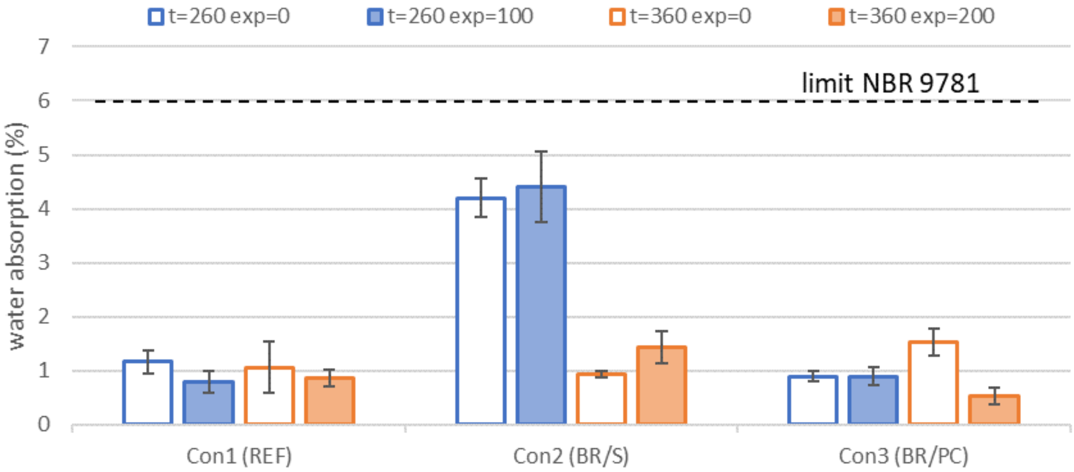

Figure 7. Water absorption of paving blocks after 0, 100, 200 days of exposure. The legend label "t" refers to curing age and "exp" refers to exposure time, both in days. The error bar represents the standard deviation.

Conc1 and Conc3 were produced maintaining the water-to-cement ratio and the paste volume. The water absorption remained similar. In the Conc2, as BR replaced sand, there was an increase in the paste volume, which could explain an increase in water absorption by capillarity. However, the increase was considerable after 100 days of exposure. This difference was not observed at 200 days. The increase in water absorption did not affect the compressive nor abrasion strengths but could impact the leaching of the soluble ions present in the concrete. These paving blocks would be classified as a non-dangerous product since no chemical specie leached was higher than the maximum limit outlined in the Brazilian standard.

A way to quantify environmental impacts related to the concrete production is to evaluate CO_2 emissions and the efficiency of binders. The main source of CO_2 emissions during the production of concretes is the clinker portion of Portland cement. These emissions have different origins, but the main contributions are of a chemical nature (the limestone decarbonation releases 0.52 ton of CO_2 for each ton of clinker) and due to fuel consumption (on the pre-calciner and rotary kiln). Considering both, for each ton of Portland clinker, up to 1 ton of CO_2 can be released into the atmosphere.

Based on the concrete formulations and the chemical composition of the used Portland cement (72% of clinker, 25% of limestone filler and 3% of gypsum), CO_2-emissions and the binder intensity were calculated (Table 4). For this calculation, the following CO_2-emissions were considered: clinker + sulfates = 860 kg/ton, limestone filler = 8 kg/ton, silica fume = 90 kg/ton, and bauxite residue = 8 kg/ton (values were adapted from [31]). It is important to mention that the CO_2-emissions related to the cement transportation and the portion coming from aggregates and admixtures were not considered, because they are negligible when compared to that emitted by the binder and are similar in the three analyzed concretes.

To allow comparisons of efficiency with other kinds of concretes, the binder intensity (BI) was also calculated. BI relates to the amount of binder (in kg) per cubic meter of concrete to obtain 1 MPa of compressive strength (in MPa), after 28 days.

Table 4. Evaluated environmental parameters

Concrete	Mean compressive strength - $f_{cm,28}$ (MPa)	Binder consumption (kg/m^3)	CO_2 emissions (kg/m^3)	Binder intensity (kg/m^3/MPa)	CO_2 index (kg/m^3/MPa)
Conc1 (REF)	57.2	356	284	6.2	5.0
Conc2 (BR/S)	54.2	356	285	6.6	5.3
Conc3 (BR/PC)	56.6	332	265	5.9	4.7

Figure 8 compares these indicators to a survey containing data from a large collection of international scientific papers and from concretes produced in Brazilian concrete batching plants. For the binder intensity, results near to the best reported practices with current technologies are observed. Concerning the CO_2-index, good results can be observed, which can be further improved if cements with a higher amount of supplementary cementitious materials, like slag or pozzolans, are used.

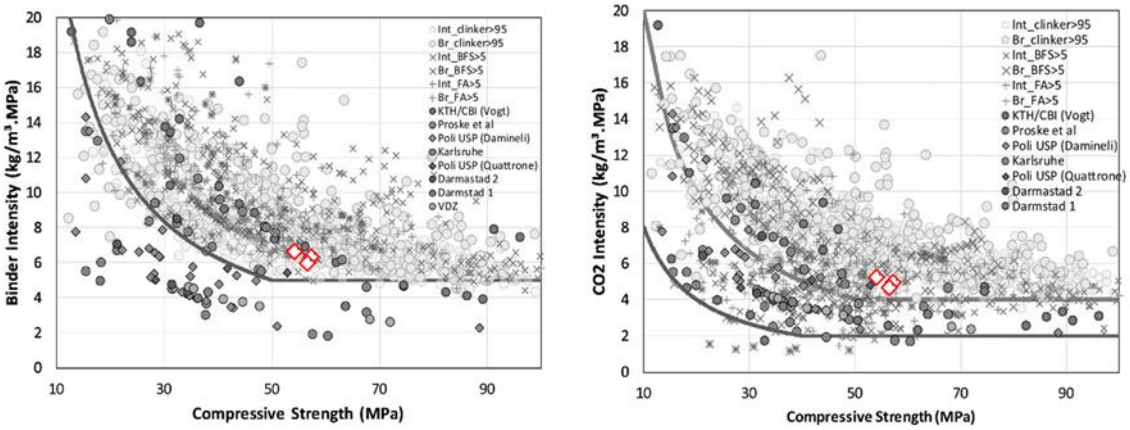

Figure 8. Benchmark of Binder intensity (on the left) and CO2-index (on the right), in function of compressive strength after 28 days. Red diamond symbols refers to the concretes evaluated in this paper. Adapted from [2]

So, pavers produced with the composition Conc2 (BR/S), where BR replaced sand, resulted in a similar CO_2-index to the Conc1 (Ref) reference composition. Despite this similarity, there are environmental gains, due to the BR consumption. For pavers produced with Conc 3 (BR/PC), where BR replaced Portland cement, in addition to BR consumption, there are eco-efficiency gains in terms of lower binder intensity and CO_2-index. Also a reduction in water consumption was observed in this concrete, representing an additional environmental gain [32].

4. Conclusion

The search for large-scale bauxite residue disposal options should certainly consider building materials, especially cementitious ones. In this case study, one of these applications, an area constructed with concrete paver blocks, was successfully performed, and the use of BR did not cause any additional difficulties to the process.

Installed inside the Hydro-Alunorte's plant in Barcarena/Brazil, the area was exposed for 200 days to weather and light traffic, and is composed of three regions with different concretes, two of which were produced with bauxite residue.

During and after the exposure time, some performance parameters were monitored on the exposed concrete blocks and compared to similar unexposed blocks. Both concretes with bauxite residue performed similar to the reference concrete without BR.

Regarding environmental aspects, the binder intensity, CO_2-emission index and water content of the concrete where bauxite residue partially replaced the sand performed similar to the reference composition. However, some improvements were obtained when part of the Portland cement was replaced by bauxite residue allowing ecoefficiency gains.

Monitoring is ongoing and will be conducted for a longer time (several years are planned), also considering aspects related to durability of product and chemical stability. So far, it can be said that the solution adopted in this case study provides a sound option for large-scale application for the bauxite residue with good technical performance and with environmental gains from different points of view.

5. Acknowledgements

The authors are thankful to Alunorte and to the Laboratory of Microstructure and Ecoefficiency of Materials, for the financial support to carry out this work.

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