

## Development of Concrete with Bauxite Residue for the Production of Paving Blocks by Casting

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### Abstract

The use of bauxite residue (BR) in concrete compositions can be a safe solution to use a large amount of this waste in construction products. However, there are literature indications that due to the higher specific area of BR compared to cement, this association can result in compositions with higher water demand, reducing the performance at the hardened state and affecting durability. One of the challenges of this solution is to produce concretes with suitable rheological properties for each production stage without compromising the hardened state properties. The main purpose of this work was to evaluate concretes with up to 30 % of BR in relation to Portland cement as a filler or a substitute to cement. Compositions were formulated using raw materials collected in Barcarena, in northern Brazil. Concretes were mixed in a rheometer to evaluate the impact of BR in the mixing process and the rheological properties were measured after mixing by applying a shear cycle. Standard rheological control was performed with slump-test according to the standard method used in concrete plants. Up to 10 % of BR as a filler and 20 % as a substitution to cement did not result in considerable changes in the fresh properties. However, with a higher amount of BR, adjustments had to be made to control consistency, which was done by adding water or superplasticizer. After 28 days of curing, compressive strength, water absorption, abrasion resistance, and permeability of the paver blocks were measured. Results show that the products made from BR comply with the Brazilian standards of road paving blocks and can be classified as suitable for conditions subject to severe abrasion effects when BR was used in addition to cement, and for lighter traffic when used in substitution.

**Keywords:** Bauxite residue, Concrete, Paving blocks, Rheology, Hardened state properties.

### 1. Introduction

Brazil is among the four largest global players in the area of bauxite reserve, bauxite extraction, and alumina production [1]. In the production process of this mining sector, 0.8 to 1.3 tonnes of bauxite residue (BR) is generated for every tonne of alumina produced depending on the quality of the ore and the digestion process [2].

Almost unused, these Bauxite residues are stored in deposits that grow exponentially as the bauxite-based industry expands [3]. Although there are more than 50 years of research and hundreds of publications and patents for the use of BR in different areas, there are still very few applications. So, the waste continues to be stored with construction and maintenance costs [4], as well as considerable investment and operational costs for dewatering the residue (e.g. filter press technology) [5] to decrease the risk of environmental contamination in the bauxite residue storage facilities.

To have a significant impact, any application or product candidate should consume an important amount of BR, demonstrate adequate performance, and consider quality, cost, and risk of contamination of the environment [3]. One sector that has the potential to meet these requirements is the construction sector with cementitious materials and components for civil construction. Compared to the world production of Portland cement (> 4 billion tonnes per year), the global generation of BR is equivalent to less than 4 % of this amount. Compared to products derived from cement, such as concretes and mortars, it represents less than 1 %.

Incorporating BR into these products seems to be a promising option to be considered [6–9]. Due to its fine size, BR tends to be used as a filler (in addition to cement) or as a partial substitute for cement or traditional cementitious materials. Several studies point to technical feasibility in the production of Portland cement clinker [10,11] or as a supplementary material to cement [4,8,12]. If possible, solutions without the need for prior treatment (such as drying, grinding, calcination, etc.) are preferable. This would simplify and make the product development proposal cheaper with a smaller environmental footprint (lower energy consumption and CO<sub>2</sub> emissions).

However, there are also indications in the literature that the higher specific surface area of BR compared to cement can result in compositions with higher water demand reducing the performance at the final stage and affecting durability [13]. One of the challenges is to produce concretes with suitable rheological properties for each production stage (mixing, transportation, and application) without compromising the properties of the final stage (hardening process). The issue of high alkalinity and in some cases the presence of heavy metals has raised concerns about the impact on health and the environment [14].

An application that is marketable on a scale that allows for the consumption of a significant fraction of the BR is the production of urban infrastructure products, such as paving blocks. There are opportunities both for paving for the light traffic (people and light vehicles) and for areas with more intense traffic subject to more abrasion. As this solution can be adapted to the local market, it reduces the need to transport raw materials over long distances. The production can take place near the BR storage area and consumer markets using concrete batching plants and casting facility on site; or a production plant can be built inside or close to the BR storage area, greatly reducing the need for transportation.

In this context, the main purpose of this work was to produce concretes, intended to produce paving blocks with up to 30 % of BR in relation to Portland cement as a filler or substitute to cement. The impacts of the introduction of BR on several properties of the fresh and hardened state were evaluated.

## **2. Experimental**

### **2.1 Materials and Concrete Compositions**

In a previous step, a reference concrete without Bauxite residue (BR) was developed (labeled as REF in Table 3). The main targets were characteristic compressive strength of 50 MPa, a slump of  $100 \pm 20$  mm, production by casting, and applicability on paver floors for heavy traffic.

Table 1 describes the granular materials used with their properties, and Figure 1 shows the particle size distributions. BR is finer than cement, indicating a potential to improve the packing of the paste. It also has a higher specific surface area.

A cement type CPV-ARI RS was used. This cement meets the requirements of the Brazilian standard ABNT NBR 16697:2018. The Bauxite residue of the Bayer process was obtained from Alunorte/Hydro in Barcarena (north of Brazil), from the active production process of alumina. It

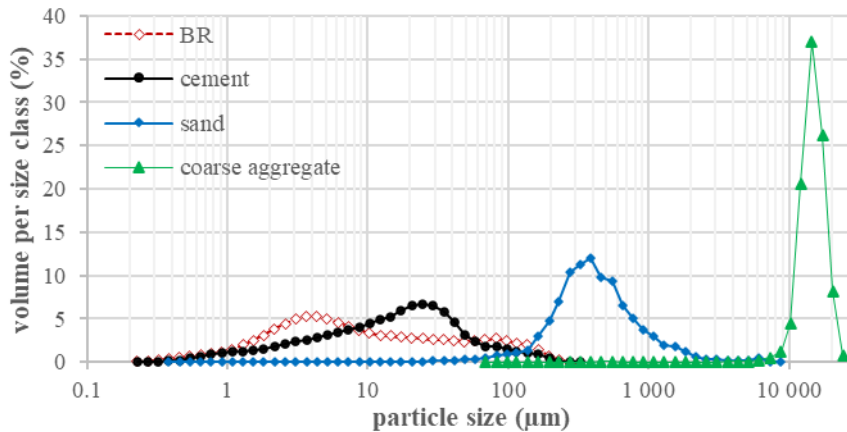
was delivered with a moisture content of 26 % and used in this condition for concrete production. Table 2 presents the chemical analysis of cement and BR.

River sand and crushed granite coarse aggregate, both from the same region of the BR production, were used as aggregates.

**Table 1. Materials and their properties.**

| Material                    | Real Density (g/cm <sup>3</sup> ) <sup>(1)</sup> | SSA (m <sup>2</sup> /g) <sup>(2)</sup> | D <sub>10</sub> / D <sub>50</sub> / D <sub>90</sub> (µm) | Water absorption (%) |
|-----------------------------|--|--|--|----------------------|
| <b>bauxite residue (BR)</b> | 2.98   | 7.41                                   | 1.58 / 7.54 / 85.1                                       | -                    |
| <b>cement</b>               | 3.13   | 4.79                                   | 2.22 / 16.2 / 58.8                                       | -                    |
| <b>natural sand</b>         | 2.65   | -                                      | 184 / 398 / 1 030  | 0.17                 |
| <b>coarse aggregate</b>     | 2.65   | -                                      | 11 646 / 15 088 / 18 939                                 | 0.45                 |

- (1) by helium gas pycnometry (AccuPyc II 1340/Micromeritics);
- (2) specific surface area: by N<sub>2</sub> adsorption and BET-model (Belsorp max/Bel Japan);
- (3) characteristic particle sizes: Laser diffraction (Helos/Sympatec) for fines; Dynamic Image Analysis (Qicpic/Sympatec) for aggregates.



**Figure 1. Particle size distribution.**

**Table 2. Chemical composition of bauxite residue and cement.**

| Oxide         | CaO  | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | SO <sub>3</sub> | MgO   | Na <sub>2</sub> O | K <sub>2</sub> O | MnO  | TiO <sub>2</sub> | LOI  |
|---------------|------|------------------|--------------------------------|--------------------------------|-----------------|-------|-------------------|------------------|------|------------------|------|
| <b>BR</b>     | 1.15 | 16.3             | 22.1                           | 36.2                           | -               | <0.10 | 9.72              | 0.03             | 0.07 | 5.27             | 8.40 |
| <b>cement</b> | 60.8 | 17.7             | 4.01                           | 3.45                           | 2.41            | 4.40  | <0.10             | 0.42             | 0.15 | 0.23             | 5.13 |

Concretes with 10 %, 20 %, and 30 % of BR were proposed, in relation to the volume of cement of the reference concrete. These BR volumes were introduced in two ways:

- addition to cement (labeled with “Ad” in Table 3): in this case, BR replaced an equivalent volume of sand, and all other materials remained constant. So, the water/cement ratio was initially kept constant at 0.42 and the water/fines ratio ranged from 0.38 to 0.33.
- partial substitution of cement (labeled with “Sub” in Table 3): in this case, BR replaced an equivalent volume of cement, and all other materials remained constant. So, the water/fines ratio was initially kept constant at 0.42 and the water/cement ratio ranged from 0.47 to 0.60.

As the modification in the composition can change the rheological behavior, an adjustment was adopted in cases where, after the initial mixing procedure, this change exceeded the pre-established limits. Two types of adjustments were considered: adjustment in the mixing water and introduction of superplasticizer (SP) additive. The concretes where adjustments were necessary

are labeled with the suffix "W" (adjustment with water) or "SP" (adjustment with superplasticizer). Concretes without a suffix in the label were not adjusted.

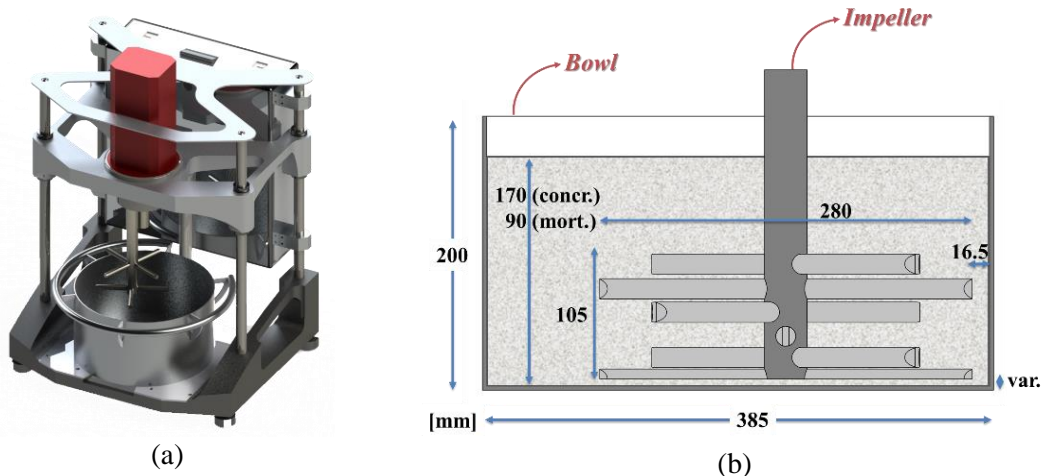
**Table 3. Concrete batch compositions (kg).**

| ID      | cement | BR   | coarse<br>aggreg. | sand  | water          | plasticizer | super-<br>plasticizer | Air <sup>(2)</sup><br>(%) | water/<br>cement | water/<br>fines |
|---------|--------|------|-------------------|-------|----------------|-------------|-----------------------|---------------------------|------------------|-----------------|
| Ref     | 7.50   | 0.00 | 20.39             | 10.59 | 3.15           | 0.049       | -                     | 0.8                       | 0.42             | 0.42            |
| 10Ad    | 7.50   | 0.72 | 20.39             | 9.95  | 3.15           | 0.049       | -                     | 2.8                       | 0.42             | 0.38            |
| 20Ad_SP | 7.50   | 1.43 | 20.39             | 9.31  | 3.15           | 0.049       | 0.013<br>(0.00)       | 3.7                       | 0.42             | 0.35            |
| 20Ad_W  | 7.50   | 1.43 | 20.39             | 9.31  | 3.39<br>(3.15) | 0.049       | -                     | 3.8                       | 0.45<br>(0.42)   | 0.35<br>(0.38)  |
| 30Ad_SP | 7.50   | 2.14 | 20.39             | 8.68  | 3.15           | 0.049       | 0.026<br>(0.00)       | 5.6                       | 0.42             | 0.33            |
| 10Sub   | 6.75   | 0.72 | 20.39             | 10.59 | 3.15           | 0.049       | -                     | 2.8                       | 0.47             | 0.42            |
| 20Sub   | 6.00   | 1.43 | 20.39             | 10.59 | 3.15           | 0.049       | -                     | 5.0                       | 0.53             | 0.42            |
| 30Sub_W | 5.25   | 2.14 | 20.39             | 10.59 | 3.34<br>(3.15) | 0.049       | -                     | 6.4                       | 0.64<br>(0.60)   | 0.45<br>(0.42)  |

- (1) values between round brackets refer to the condition before rheological adjustment.
- (2) Air content after final mixing and, if necessary, after adjustments.

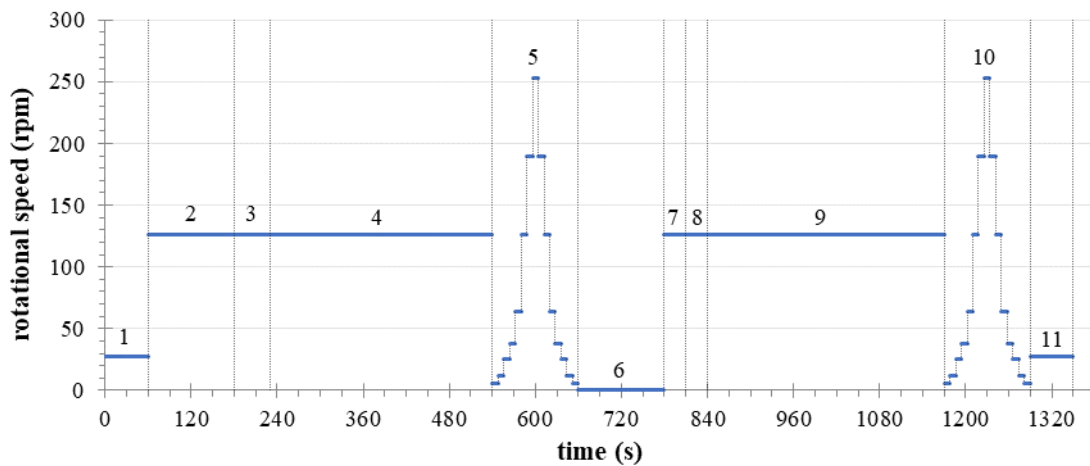
## 2.2 Mixing and Fresh State Testing

Concretes were mixed with a PHESO (Calmetrix) rheometer using an attritor impeller (Figure 2) to evaluate the impact of the BR introduction along the mixing process. This was performed in two steps: firstly, mortar was mixed and rheology measured (steps 1 to 5 in Figure 3), then coarse aggregates were added to obtain the concrete (steps 7 to 11). After final homogenization, other tests were carried out on the mortar mixture (rheometry, slump test, and density for incorporated air evaluation).



**Figure 2. Rheometer: general view (a); details of mixing device (b).**

To determine the rheological behavior of mortar and concrete shear cycle tests were performed (steps 5 and 10 in Figure 3). Each cycle consists of an acceleration stage (8 steps of 8 seconds each, with rotations increasing from 6 to 250 rpm) followed by a similar deceleration stage.

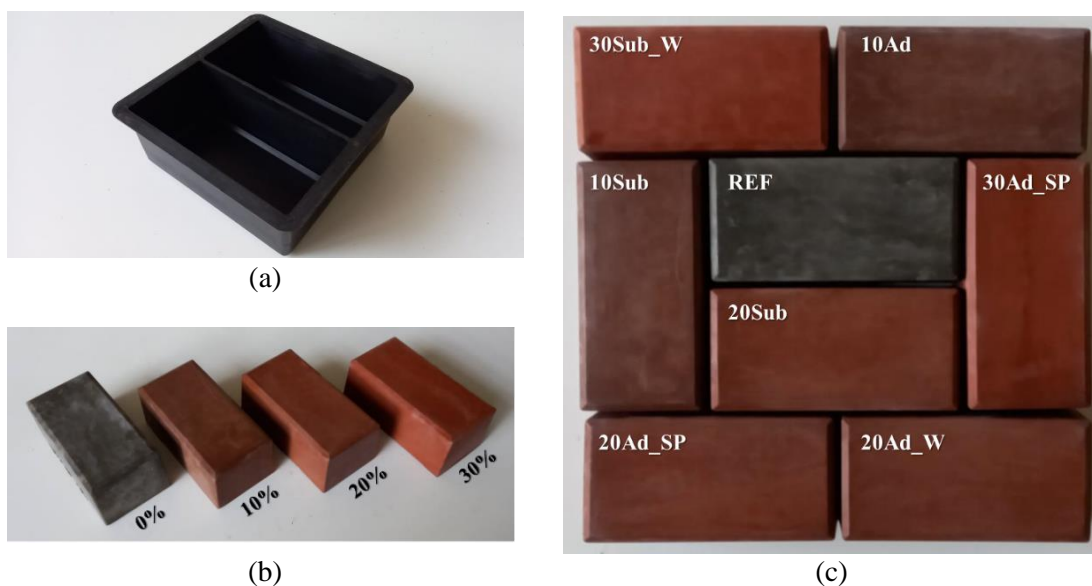


**Figure 3. Test program sequence: (1) positioning of the rheometer; (2) homogenization; (3) addition of water and additive; (4) mortar mixing; (5) mortar shear cycle; (6) stop; (7) repositioning of the rheometer; (8) coarse aggregates addition; (9) concrete mixing; (10) concrete shear cycle; (11) returning of the rheometer.**

Initially, all concretes with BR were tested with the same water amount as the reference concrete, to evaluate the impact of the BR introduction on rheological properties. Adjustments were also made to adjust the workability, based on the mixing torque measured by the rheometer. Water or superplasticizer was added until the mixing torque (125 rpm) was within the limits pre-established in the reference concrete.

### 2.3 Concrete Paving Blocks Testing

Concrete paving blocks were produced by casting in plastic molds (Figure 4-a) and compacted with a vibration table. After 24 hours of curing in the molds, the blocks were demolded and stored in a wet chamber to cure for 28 days. Figure 4 (b and c) shows the produced paver blocks, illustrating the impact of BR in color.



**Figure 4. Casting mold and concrete paving blocks at various content of BR.**

Concrete paving blocks properties were determined according to the prescription of Brazilian standard (ABNT NBR 9781:2013) designed to evaluate concrete interlocking paving units subject to pedestrian traffic, vehicles equipped with pneumatic tires, and storage areas. The main evaluations required by this standard are compressive strength, water absorption, and abrasion wear. Permeability to air was also evaluated with an in-situ vacuum decay permeameter as additional durability correlated parameter.

### 3. Results and Discussion

#### 3.1 Fresh State Results

Figure 5 shows the shear cycle results for the reference concrete. On the left, the two stages of the shear cycle (acceleration = continuous line; deceleration = dashed line), two notable points (maximum and minimum rotation), and the hysteresis area (area between the acceleration and deceleration stages) are illustrated. On the right, one of the stages (acceleration) is illustrated, highlighting the experimental points (90 % confidence interval indicated by the error bars) to which mathematical models were fitted using least squares regression.

Concretes are often described as having a Bingham [15] fluid behavior, which has a linear “shear stress versus shear rate” relation after an initial shear stress threshold (yield stress) has been reached (Equation (1)). But not always the shear stress increase is proportional to the shear rate increase. In these cases, other models are more suitable, like the Herschel-Bulkley model [16], which also allows quantifying the degree of shear thickening ( $n > 1$ ) or thinning ( $n < 1$ ) of the suspension (Equation (2)).

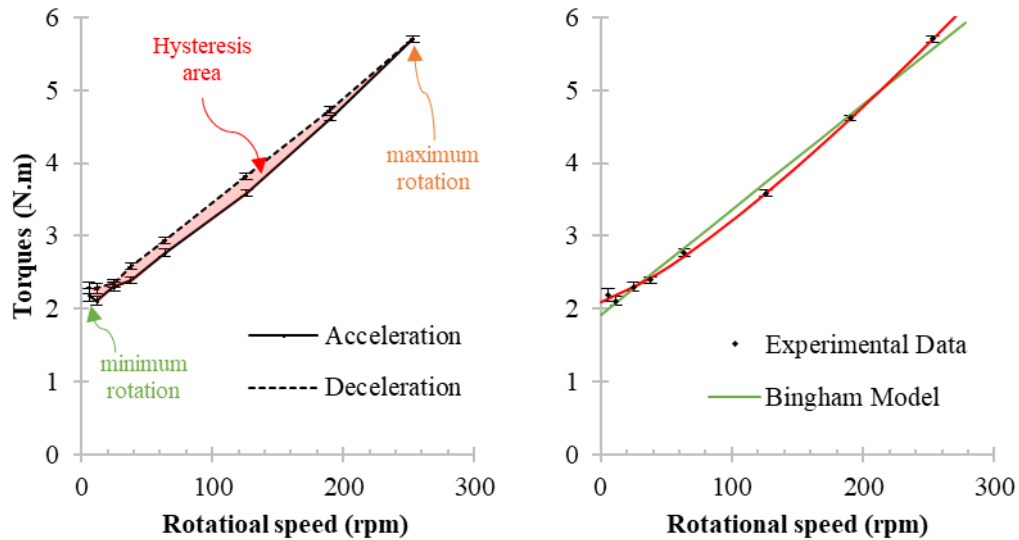


Figure 5. Reference concrete shear cycle results and rheological analysis models.

$$T = T_0 + h_B R \quad (1)$$

$$T = T_0 + h_{HB} R^n \quad (2)$$

where:

$T$  Torque, N.m

$T_0$  Yield torque, N.m

$R$  Rotational speed, rpm

$h_B$  Constant equivalent to plastic viscosity in the Bingham model, N.m/rpm

$h_{HB}$  Constant equivalent to the consistency index in the Herschel-Bulkley model, N.m/rpm<sup>n</sup>

$n$  flow behavior index in the Herschel-Bulkley model, dimensionless

Figure 5 shows that the reference concrete exhibits a minimum torque to start flowing (yield torque) and then an almost linear behavior in the tested shear range. The Bingham model fitted to the experimental data gives a high coefficient of determination ( $R^2 = 0.992$  in the acceleration stage;  $R^2 = 0.997$  in the deceleration stage) and the Herschel-Bulkley flow behavior index is just slightly higher than 1 ( $n = 1.26$  acceleration;  $n = 1.12$  deceleration).

Some of the most representative shear cycle results are shown in Figure 6. As can be seen, the behavior is almost linear and, in most cases, slightly rheopectic (the deceleration stage has higher torque than acceleration). The following analysis concentrates mostly on the deceleration curve (because it has gone through more shearing, resulting in a more homogeneous and dispersed condition) and considered Bingham rheological model. The main experimental values and model parameters, for both mortar and concrete (before and after adjustments), are shown in Table 4.

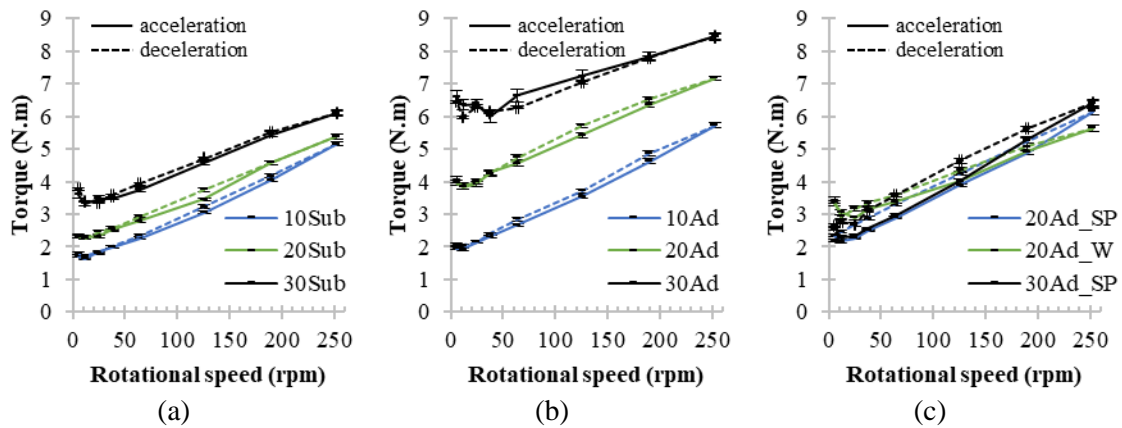


Figure 6. Shear cycle results: (a) substitution; (b) addition without adjustment; (c) addition with adjustment.

Table 4. Rheological parameters of tested mortars and concretes.

| Phase                 | ID      | T <sub>max</sub><br>(N.m) | T <sub>min,d</sub><br>(N.m) | T <sub>0B</sub><br>(N.m) | h <sub>B</sub><br>(N.m/rpm) | R <sup>2</sup> | n    | Hyst.<br>(%) | T <sub>mix</sub><br>(N.m) | Slump<br>(mm) |
|-----------------------|---------|---------------------------|-----------------------------|--------------------------|-----------------------------|----------------|------|--------------|---------------------------|---------------|
| Mortar                | Ref     | 0.506                     | 0.120                       | 0.079                    | 0.00156                     | 0.971          | 1.60 | 94           |                           | -             |
|                       | 10Ad    | 0.591                     | 0.116                       | 0.090                    | 0.00198                     | 0.986          | 1.20 | 95           |                           | -             |
|                       | 20Ad_SP | 1.106                     | 0.448                       | 0.440                    | 0.00255                     | 0.983          | 1.06 | 98           |                           | -             |
|                       | 20Ad_W  | 1.045                     | 0.451                       | 0.414                    | 0.00244                     | 0.995          | 1.17 | 101          |                           | -             |
|                       | 30Ad_SP | 1.700                     | 1.082                       | 1.058                    | 0.00265                     | 0.988          | 0.79 | 100          |                           | -             |
|                       | 10Sub   | 0.480                     | 0.167                       | 0.092                    | 0.00142                     | 0.910          | 1.77 | 100          |                           | -             |
|                       | 20Sub   | 0.588                     | 0.190                       | 0.145                    | 0.00161                     | 0.966          | 1.67 | 92           |                           | -             |
| Non Adjusted Concrete | 30Sub_W | 0.818                     | 0.437                       | 0.391                    | 0.00164                     | 0.986          | 1.15 | 98           |                           | -             |
|                       | Ref     | 5.700                     | 2.289                       | 2.083                    | 0.0141                      | 0.997          | 1.12 | 104          | 3.62                      | 105           |
|                       | 10Ad    | 5.716                     | 2.061                       | 1.856                    | 0.0154                      | 0.997          | 1.05 | 104          | 3.61                      | 120           |
|                       | 20Ad_SP | 7.166                     | 3.946                       | 3.777                    | 0.0140                      | 0.991          | 0.87 | 103          | 5.51                      | 55            |
|                       | 20Ad_W  | 7.334                     | 4.099                       | 3.907                    | 0.0139                      | 0.994          | 0.95 | 102          | 5.62                      | 50            |
|                       | 30Ad_SP | 8.448                     | 6.449                       | 5.968                    | 0.0094                      | 0.937          | 1.52 | 98           | 7.09                      | 0             |
|                       | 10Sub   | 5.159                     | 1.788                       | 1.524                    | 0.0141                      | 0.995          | 1.19 | 103          | 3.04                      | 140           |
| Adjusted Concrete     | 20Sub   | 5.388                     | 2.316                       | 2.141                    | 0.0128                      | 0.998          | 1.07 | 103          | 3.60                      | 95            |
|                       | 30Sub_W | 6.100                     | 3.773                       | 3.300                    | 0.0111                      | 0.966          | 1.20 | 102          | 4.62                      | 70            |
|                       | 20Ad_SP | 6.144                     | 2.557                       | 2.348                    | 0.0151                      | 0.998          | 1.03 | 108          | 3.86                      | 110           |
|                       | 20Ad_W  | 5.648                     | 3.431                       | 3.001                    | 0.0106                      | 0.970          | 1.14 | 105          | 3.97                      | 80            |
|                       | 30Ad_SP | 6.402                     | 2.654                       | 2.521                    | 0.0158                      | 0.994          | 0.92 | 110          | 4.07                      | 100           |
|                       | 30Sub_W | 4.975                     | 2.756                       | 2.448                    | 0.0098                      | 0.985          | 1.24 | 103          | 3.39                      | 90            |

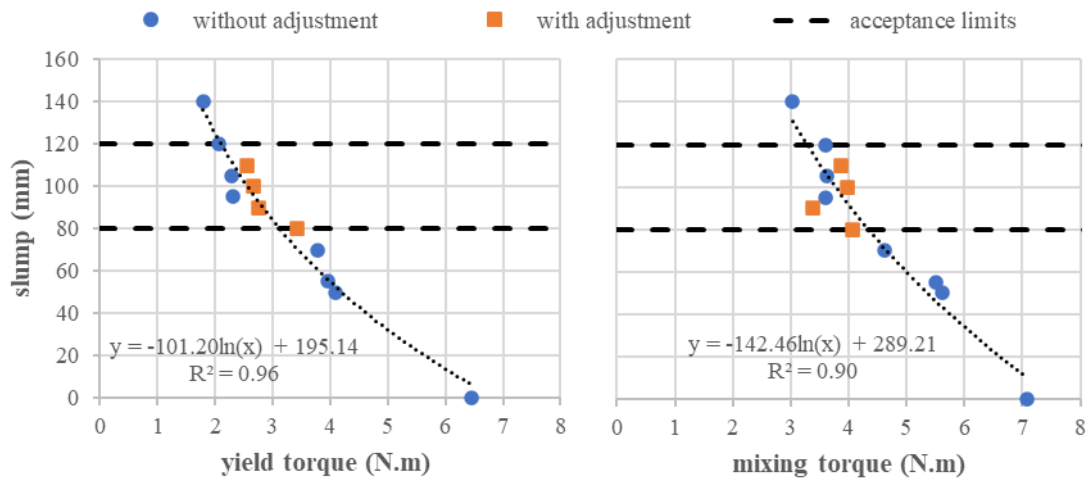
T<sub>max</sub> – Experimental torque at highest rotational speed (250 rpm);

T<sub>min,d</sub> – Experimental torque at slowest rotational speed (6 rpm);

T<sub>0B</sub> – Yield torque, calculated according to Bingham Model;

$h_B$  - Constant equivalent to plastic viscosity in the Bingham model;  
 $R^2$  - coefficient of determination for Bingham model;  
 $N$  - flow behavior index in the Herschel-Bulkley model;  
 Hyst - Hysteresis area (calculated as ratio between area under deceleration and acceleration curves);  
 $T_{mix}$  - Torque at final mixing process (at 125 rpm).

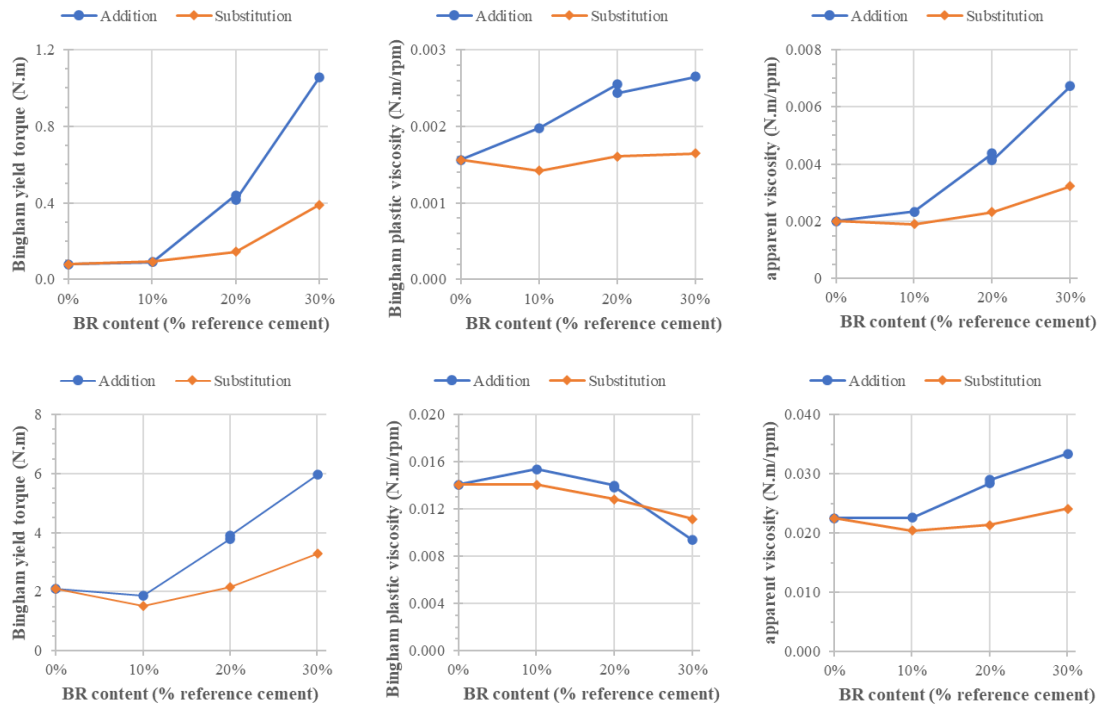
Figure 7 (left) shows the good match between slump and yield torque. The specified  $100 \pm 20$  mm slump acceptance range corresponds to  $2.6 \pm 0.5$  N.m of yield torque. As all these concretes have the same mortar content, even mixing torque correlates well with slump (Figure 7 - right), leading to an acceptance interval in terms of mixing torque of  $3.8 \pm 0.5$  N.m. This has practical importance because it allows to adjust the formulation until mixing torque target range is achieved. This type of control can be done not only in rheometers but also in commercial scale mixers [17].



**Figure 7. Slump and rheometry correspondence: yield torque (left); mixing torque (right).**

The effects of introducing BR into mortars and concretes are presented in Figure 8. As already described, two BR introduction modes were studied. In the so-called “Addition” mode, the BR partially replaced sand, while cement remained fixed, resulting in a higher content of fines and paste. In the “Substitution” mode, the addition of BR took place by partially replacing the cement, keeping the volume of fines (cement + BR) and paste fixed.

Broadly speaking, mortars and concrete behave similarly. For the yield torque, there is little effect up to 10 % addition and up to 20 % replacement. For concrete with 10 % BR replacement a slight yield torque reduction can be observed with slump test above the specified limit (140 mm). This may be due to the granulometric difference between cement and BR, which provides an improvement in particle packing. From 10 % of BR, there is a linear increase in the flow torque with the content of BR. Even with the pastes solids content being maintained in the substitution mode the yield torque increases due to the increase in the surface area and mobility reduction of the suspension. In addition, mode, this is potentiated by the pastes solids concentration increase.



**Figure 8. Effect of BR on rheological parameters of mortars (top) and concretes (bottom): Bingham yield torque (left); Bingham plastic viscosity (center); apparent viscosity at highest rotation (right).**

For mortars, plastic viscosity did not change much when BR substitutes cement. In these cases, the paste solid concentration does not change. In addition mode, there is a linear increase in plastic viscosity, accompanying the increase in solids concentration. Thus, in mortar, there seems to be a strong relationship between paste solids concentration and viscosity. In concretes, a similar effect is observed for low levels (up to 10 %) of BR. But for higher BR content there is a trend reversal. Especially in addition mode, where the BR introduction replaces sand, a higher amount of paste is available, which allows greater distance and lubrication between the aggregate particles reducing energy dissipation during shear and resulting in lower viscosity.

The apparent viscosity at high shear rates (right charts in Figure 8) is a result of the combination of yield torque and plastic viscosity. Even at high shear rates, the elevation of yield torque is more relevant than the reductions in plastic viscosity observed in some concretes. For low shear applications, up to 10 % of BR as addition, and 20 % as substitution of cement, did not result in considerable rheological changes. For higher shear applications, even 30 % of BR substitution can be considered.

However, with a higher amount of BR, adjustments of the consistency were necessary, which was done in two different ways: by adding water or superplasticizer. The adjustment was based on slump specifications ( $100 \pm 20$  mm), which correlates with torques at low rotation speed. But the adjustment at low shear rates does not mean that the same occurs at higher shear. As can be seen in Figure 9, adjustment in water tends to reduce plastic viscosity, while SP addition tends to increase viscosity. The biggest change can be seen with 30 % of BR addition, resulting in a 70 % viscosity increase. This means that at high shear rates, correction with additive can result in rheology demanding compositions, even if adequate at low rates. Although the percentages studied in this work did not result in important changes, this characteristic needs to be considered if higher BR content is to be used in the future.

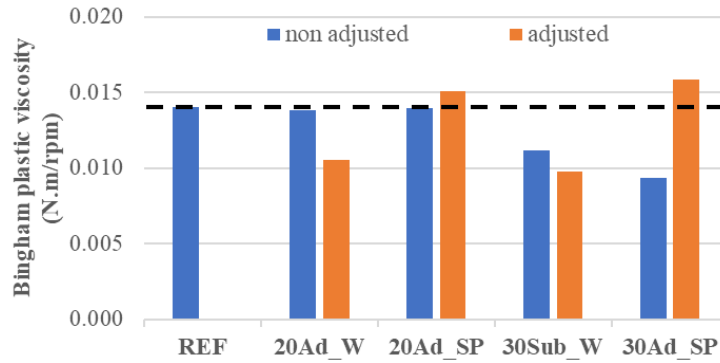


Figure 9. Effect of different adjustment methods on plastic viscosity.

### 3.2 Hardened State Results

Formulation decisions to meet fresh state requirements affect the microstructure of concretes and may have effects on the properties in the hardened state. Maintaining the water/cement ratio is a common decision, which aims to preserve the porosity of the hardened material, and thus strength and durability. However, as seen in the previous step, introducing BR without changing cement and water can affect and even make the application of concrete unfeasible, requiring adjustments. The effect of introducing BR on some hardened state properties was evaluated after 28 days of curing. Compressive strength, water absorption, modulus of elasticity, abrasion resistance, and permeability of the produced pavers were measured and are reported in Table 5. As an eco-efficiency indicator, binder index (bi) [18] was calculated according to Equation (3).

$$bi = \frac{B}{f_p} \quad (3)$$

where:

- $bi$  binder intensity,  $\text{kg/m}^3 \cdot \text{MPa}$
- $B$  binder content, not including non-reactive fillers in cement,  $\text{kg/m}^3$
- $f_p$  compressive strength, MPa

Table 5. Hardened state concrete properties (kg).

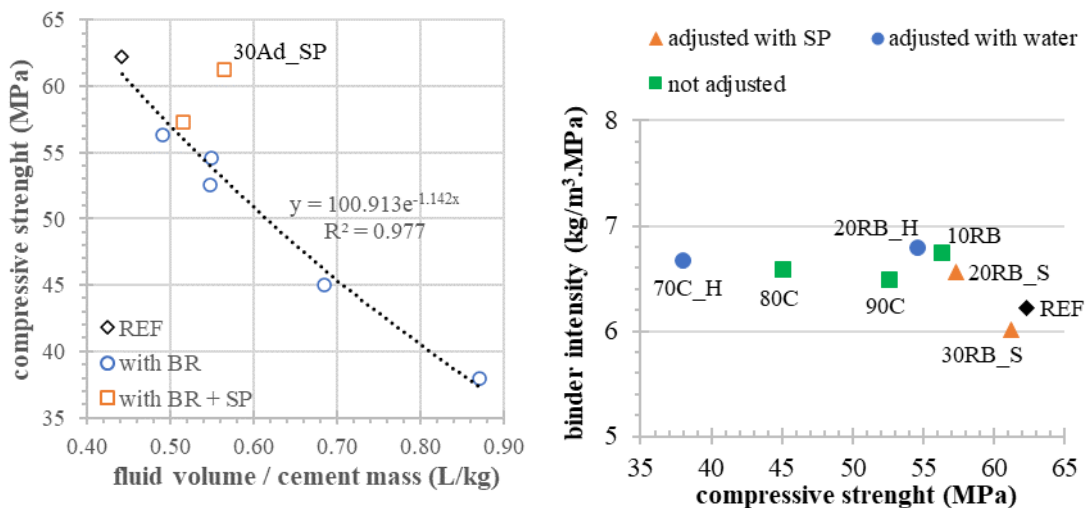
| ID      | compressive strength (MPa) | binder intensity ( $\text{kg/m}^3 \cdot \text{MPa}$ ) | modulus of elasticity (GPa) | abrasion wear width (mm) | water absorption (%) | permeability coefficient ( $10^{-14} \text{ m}^2$ ) |
|---------|----------------------------|---|-----------------------------|--------------------------|----------------------|---|
| Ref     | 62.3                       | 6.2   | 44.7                        | 19.1                     | 3.66                 | 6.3   |
| 10Ad    | 56.3                       | 6.7   | 44.9                        | 20.0                     | 3.75                 | 6.3   |
| 20Ad_SP | 57.3                       | 6.6   | 48.9                        | 20.0                     | 3.63                 | 7.2   |
| 20Ad_W  | 54.6                       | 6.8   | 46.9                        | 19.1                     | 3.85                 | 8.4   |
| 30Ad_SP | 61.2                       | 6.0   | 48.6                        | 20.3                     | 3.41                 | 5.2   |
| 10Sub   | 52.6                       | 6.5   | 42.6                        | 19.9                     | 4.06                 | 8.6   |
| 20Sub   | 45.0                       | 6.6   | 43.9                        | 19.3                     | 4.11                 | 14.1  |
| 30Sub_W | 38.0                       | 6.7   | 38.3                        | 20.3                     | 4.71                 | 18.5  |

All concretes with BR showed lower compressive strength than the reference concrete (no BR). Although the reduction was not so high, this occurred even in concretes where BR was used as an addition to cement and the water/cement ratio remained constant. This seems to be related to the increase in air content (Table 3) as higher BR content was used. On the other hand, in the substitution mode, the impact was higher, as the reduction in binder content is accompanied by an increase in the water/cement ratio.

A good correlation can be observed by describing compressive strength as a function of fluid volume (water + air) to cement consumption, (Figure 10-left). All concretes fit very well to this

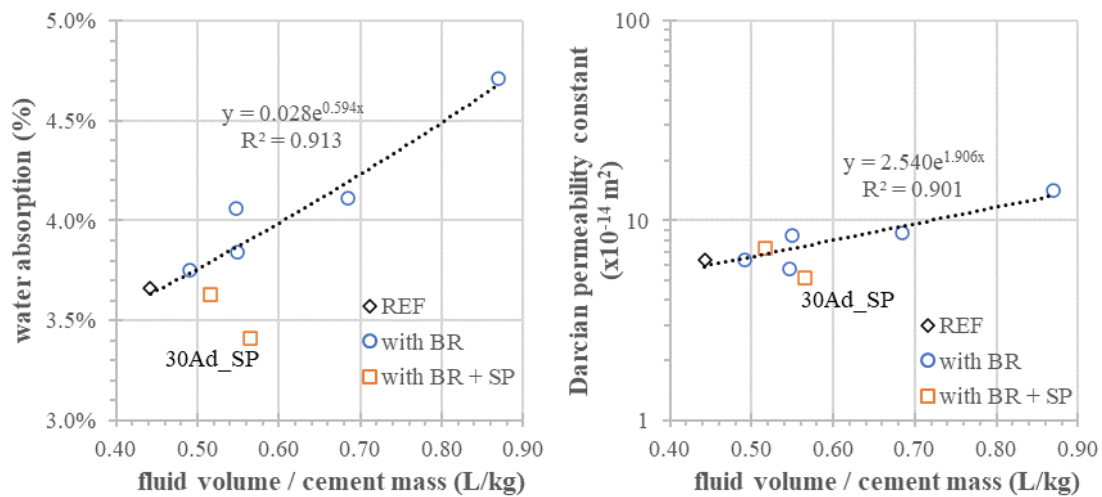
exponential model, except the concrete with 30 % BR addition, where a considerable deviation (about + 8 MPa) can be noted. With this performance improvement, this concrete achieved only slightly lower strength than the reference concrete, despite the increase in air content. The hypothesis that can explain this behavior is that the introduction of a higher superplasticizer content was able to promote better dispersion. The superplasticizer acts not only on the dispersion of the BR but also on the cement particles, which have a high tendency to flocculate due to the heterogeneity of surface charges. A more effective dispersion can break this flocculated state, releasing a considerable portion of water into the system. Although this does not reduce the total available water, it can generate a more homogeneous system, with a more refined pore system, which can contribute to the reduction of defects and thus increase strength.

Figure 10 (right) shows the binder efficiency obtained in concrete paving blocks with BR. In general, the introduction of BR slightly reduced the efficiency (average of 6.5 kg/m<sup>3</sup>.MPa) compared to the reference (6.2 kg/m<sup>3</sup>.MPa). The variation of this index was small regardless of the BR, water, and superplasticizer content. Probably the higher air content contributed to this elevation of the binder intensity. However, the concrete with 30 % addition, adjusted with superplasticizer, stands out. The better dispersion increased strength and thus the binder efficiency (6.0 kg/m<sup>3</sup>.MPa), resulting even slightly better than the reference concrete. This is an indication that the concept of dispersion is important in the search for better eco-efficiency.



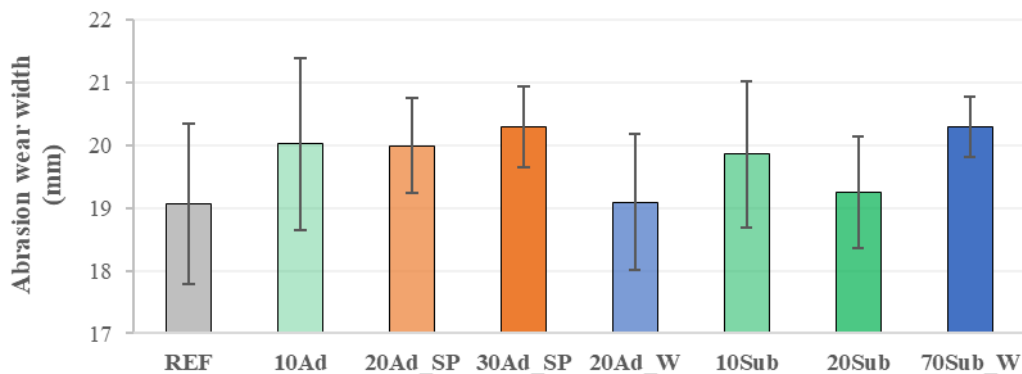
**Figure 10. Compressive strength (left) and binder intensity (right). All concretes, except 30Ad\_SP, were considered in the trendline.**

Water absorption, permeability, and elasticity modulus follow similar trends to compressive strength, indicating that the porous capillary structure and air incorporation control the mechanical and some durability-related properties. Maintaining water/cement is an initial approach, but more effective dispersion can provide improvements, even in concretes with higher amounts of BR.



**Figure 11. Water absorption (left) and permeability coefficient (right). All concretes, except 30Ad\_SP, were considered in the trendlines.**

Abrasion does not seem to be governed by porosity, like the other evaluated properties. Some concretes with BR had similar results as the reference concrete, and the others only slightly higher values. As the experimental variability is relatively high (the error bars represent a 90 % confidence interval) it is not possible to state that there are statistically relevant differences.



**Figure 12. Abrasion wear. Error bars represent 90 % confidence interval.**

Results show that the materials produced with BR comply with the Brazilian standard for road paving blocks and be a solution for light and heavy traffic. In terms of water absorption, all concretes are under the maximum limit of 5 %. The measured compressive strength makes it possible to classify the concretes as suitable for heavy traffic (characteristic strength greater than 50 MPa) where BR was used as an addition to cement. Concretes, where cement was partially replaced by BR, fell into the light traffic class. By adopting appropriate strategies, even 30 % of BR could be used in these two classes. Regarding abrasion, the concretes are on the boundary between light and heavy traffic, established as 20 mm of wear width in the standard. As this result does not seem to depend on the BR content, it is recommended that further investigations be carried out, including the contribution of the aggregates to wear. If high traffic applications are sought, it would be desirable to achieve results more clearly below 20 mm, to reduce the risk of premature wear of the products. In any case, the present investigation indicates the technical feasibility from the rheological and mechanical point of view. For wider and safer applications, additional product criteria need to be investigated such as leaching, efflorescence, steel bar corrosion, alkali-silica reaction, and others.

#### 4. Conclusion

Several concretes were developed to produce paving blocks. Strategies for adding and replacing cement with BR were evaluated, as well as rheological adjustments with water and superplasticizer additive were tested.

In the study carried out, up to 20 % replacement and 10 % addition resulted in little effect on rheological properties, indicating that the improvement in paste packing may have compensated for the increase in the surface area resulting from BR addition. For higher BR percentages, the results showed an important increase in yield stress, particularly in the case of 30 % addition. The plastic viscosity remained similar and, in some cases, even slightly lower than the reference concrete. This reduction, however, is not enough to counterbalance the increase in yield stress, and thus, at high shear rates, an increase in apparent viscosity is still observed in concretes with higher BR contents.

In some cases, the rheological properties changed so much that it would compromise casting of concrete. In these concretes, it was possible to add water or superplasticizer, thus getting similar slump, flow torque, and mixing torque at intermediate rotations. As a side effect, plastic viscosity reduced when adjusted with water and increased if adjusted with superplasticizer. This increase would require careful consideration if higher levels of RB are to be used.

Most properties in the hardened state showed similar trends, mainly depending on the water/cement ratio and air content. The air content followed the introduced BR content, which needs to be better evaluated and controlled in future research.

It was possible to obtain concretes with strengths between 38 and 61 MPa, with up to 30 % BR in relation to the cement mass of the reference concrete. This is a significant quantity considering the global production of cement and concrete. Also, supplementary additions in composite cements, if these additions are not reactive, usually do not exceed 25 %.

Evaluating the eco-efficiency of the concretes, based on the binder intensity (ratio between binder consumption and strength performance), shows that the concretes have values between 6.0 and 6.8 kg/m<sup>3</sup>/MPa, similar to the reference concrete (6.2 kg/m<sup>3</sup>/MPa). The best result refers to the concrete with 30 % BR in addition to the cement: the increase in performance was attributed to a better dispersion when adjusted with a superplasticizer additive to improve workability.

All the paving blocks produced with BR comply with the Brazilian standards of road paving blocks. The products could be classified as suitable for areas subject to severe abrasion when BR was used in addition to cement, and for lighter traffic when used in substitution. More general use of these concretes, even in other applications, may be feasible, provided that additional performance criteria are assessed successfully such as leaching, efflorescence, steel bar corrosion, alkali-silica reaction, and others.

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