BR13 - Application of Synthetic Aggregate from Bauxite Residue in Structural Elements

Bruno Viegas[1], Mailson Vilhena[2], Marcelo Picanço[3], Dênio Oliveira[4], Alcebíades Macêdo[5], Edilson Magalhães[6], João Quaresma[7], Emanuel Macêdo[8], José Souza[9], Darllan Pinheiro[10], Marcelo Montini[11], Raphael Costa[12]

1. Professor
2. Student
Faculty of Biotechnology, Federal University of Pará, Belém, Brazil
3. Professor
4. Professor
5. Professor
Faculty of Civil Engineering, Federal University of Pará, Belém, Brazil
6. Professor
7. Professor
8. Professor
9. Professor
Faculty of Chemical Engineering, Federal University of Pará, Belém, Brazil
10. R&D specialist
11. Chemical Consultant
12. Head of Technology B&A
Norsk Hydro Brazil, Belém, Pará, Brazil
Corresponding author: viegasmbruno@gmail.com

Abstract

Synthetic aggregate has been used successfully in various fields of the construction industry. Because it is a manufactured product, its properties can be suitably modified depending on the intended applications. In this work, bauxite residue, clay, and silica were used to produce synthetic aggregate, whose specimens were made in different proportions of these raw materials and sintered at 1200 ºC. Leaching and chloride penetration tests were performed, to predict the behavior of the aggregates when submitted to natural conditions. The synthetic aggregates were applied in beams and slabs, where results indicated that the process performed and the products obtained are acceptable by the technical criteria for application in the construction industry, besides presenting a high capacity for the reuse of bauxite residue.

Keywords: Bauxite residue, Synthetic aggregate, Construction industry, Beam, Slab.

1. Introduction

The accelerated growth of the construction industry has resulted in a significant shortage of raw materials for the production of concrete, such as natural aggregates. The main sources of aggregates used come from rivers, seas, deserts, and industrialized sand. River sand or pebbles, for example, are used in construction but are becoming scarce worldwide due to depletion and environmental constraints [1].

The main component of concrete is inert aggregate, which is held together by cement. Aggregates can be composed of a wide variety of materials and are classified as coarse or fine [2]. The concrete mix is composed of 70 to 80 % volume of fine and coarse aggregates, which results in a constant decrease of natural sources due to the large amount used [3].

Synthetic aggregate is an alternative to natural aggregate, and the main type produced is lightweight expanded clay, which is mostly made up of silica (SO_2) in the morphological form of α-quartz; magnesium silicate ($Mg(SiO_4)$) and magnesium aluminum oxide ($MgAl_2O_4$) in spinel form [4]. In the production of the aggregate, different types of industrial and mineral waste can be used, such as gold mining tailings and limestone waste [5], bauxite waste and acid-leaching tailings [6], bauxite residue, fly ash and sodium silicate solution [1], among others.

This aggregate is among the materials commonly applied in engineering projects in countries such as Norway, Russia, Germany, Italy, Denmark, Switzerland, Finland, Portugal, United Kingdom, Iran, and India [7]. The production of this aggregate is done by heating clay in rotary kilns. During the production process, clay expansion results in grains with a heterogeneous structure composed of a rigid outer shell and a highly porous core, giving the material its characteristic lightness [8].

Due to the manufactured nature of the product, its characteristics, including grain weight density, diameter, and thickness, may vary depending on the desired specifications for the material's end use. In the construction industry, its main applications include its use as a lightweight filler in geotechnical works and in the production of lightweight concrete [8].

Synthetic aggregates are produced from clay or waste by-products, resulting in a product with a specific weight lower than that of crushed stone and with high water absorption. The sintering process is generally carried out between 1100 and 1350 ºC. The raw materials used are classified into three groups: natural, miscellaneous waste, or a combination of residues and natural raw materials with additives [9].

Synthetic aggregates have attracted considerable attention due to their diversity, which enables the beneficial use of these materials for various applications [3]. Synthetic aggregates uses can not only delay the extraction of natural aggregates but also minimize environmental pollution. Thus, the use of industrial solid waste in the production of these materials represents an effective strategy to reduce the consumption of non-renewable resources [10].

Bauxite residue (BR) is generated from the Bayer process (alumina production). This residue has a complex chemical and mineralogical composition, which depends on the origin of the bauxite ore and operating conditions during the Bayer process [11]. Due to the different oxides present in its composition [12,13], BR can be an important raw material for the production of synthetic aggregates [2]. In this context, the present work aims to carry out the production of synthetic aggregates with bauxite residue, clay, and silica for application in beams and slabs.

2. Materials and Methods

Bauxite residue, clay, and silica were dried in an oven at a temperature of 105 ºC for 24 h. Subsequently, the materials underwent comminution in a ball mill, as shown in Figure 1.

The drying and comminution processes aimed to adjust the humidity and granulometry of the raw materials, respectively. The clay in the production of synthetic aggregate aimed to greater plasticity to the mixture, keeping the material cohesive. While silica was used to promote better formation of mullite and the glassy phase, according to research published in the literature [14-16]. The production stage, as well as the use of raw materials, was based on a previous study in which the authors evaluated the chemical, mineralogical and mechanical characteristics of the synthetic aggregate using bauxite residue [17].

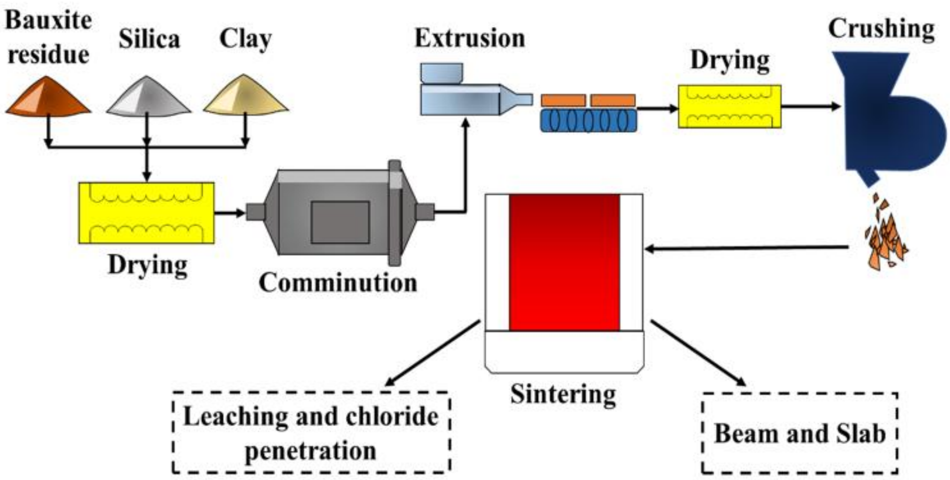

Figure 1. Synthetic aggregate production process.

After the preparation phase, illustrated in Figure 1, the raw materials were weighed and homogenized in different proportions to produce three synthetic aggregates: AGG70, AGG80, and AGG90. The amount of bauxite residue ranged from 70 to 75 % by weight for AGG70, 80 to 85 % by weight for AGG80, and 90 to 95 % by weight for AGG90. Clay was kept constant at 5 % by weight in all samples, while silica ranged from 10 to 25 % by weight. With the aid of a mechanical mixer, water was added in a predefined amount until the formation of a ceramic mass, which was subsequently extruded to obtain the final product.

During the extrusion step, the ceramic mass was molded into rectangular blocks and subsequently to a drying process to remove moisture. The blocks were processed in a jaw crusher using a predefined jaw opening, resulting in a material with varied granulometry (size 1 - 25 mm). The aggregates were sintered in an electric furnace at a temperature of 1200 °C, with a heating rate of 10 °C/min for 3 h. The apparent density of the produced aggregates is in the range of 1.5 to 2.5 g/cm^3, the apparent porosity in the range of 0.21 to 15.34 % and the apparent water absorption in the range of 0.12 to 1.66 %. The chemical and mineralogical characteristics of these aggregates were presented in a previous study [17], which identified similar compounds to those present in lightweight expanded clay aggregates (SiO_2, Al_2O_3, CaO and Fe_2O_3) [18]. Figure 2 shows the synthetic aggregates produced.

Figure 2. Sintered aggregates.

After the sintering stage, leaching and chloride penetration tests were carried out in the produced aggregates. The leaching tests were carried out to observe and predict the behavior of the aggregates when subjected to natural leaching agents. Leaching was evaluated according to the Brazilian standard ABNT NBR 10005:2004 [19], which addresses the requirements for obtaining a leached extract from solid waste. The experiments were performed in duplicate.

For the chloride penetration tests, prismatic specimens measuring 8×8×15 cm were manufactured (Figure 3). Analyzes were performed in duplicate and compared to a reference aggregate (pebble). The specimens were immersed in a 3M NaCl solution for a period of 28 days, at a temperature of 23 ± 2 °C, in a container measuring 45×32×24 cm.

Figure 3. Specimens for the chloride penetration test.

Synthetic aggregates produced were applicated in to structural elements: beams and slabs. Four reinforced concrete beams of the same span and section were made, divided into pairs, two of which were made of conventional concrete (pebble) and the other two of synthetic aggregate (AGG80). The same conformation used for the beams was also carried out for the slabs, whose dimensions were 1400×1400×120 mm.

3. Results and Discussion

3.1 Leaching

Table 1 presents the results of the analyzes carried out on the leached extracts of the AGG70, AGG80, and AGG90 samples.

Table 1. Sodium concentration in the leachate extract of synthetic aggregates.

Sample	Sodium concentration (mg/L)
AGG70	13.75
AGG80	16.62
AGG90	18.32

The data presented in Table 1 demonstrate that the sodium concentrations in the leached extracts are in the range of 13.75 to 18.32 mg/L, which are lower than the maximum limit established by the Brazilian standard ABNT NBR 10004:2004 for solubilization tests (200 mg/L) [20]. The values in Table 1 can be attributed to solid-state reactions that occur during phase transformations in the synthetic aggregate. These reactions convert sodium hydroxide (NaOH) into glass, resulting in an inert material and eliminating the possibility of effluent generation after sintering.

3.2 Chloride Penetration

Figure 4 shows the results of the bauxite residue synthetic aggregates compared to the reference aggregate (pebble) for the chloride penetration tests.

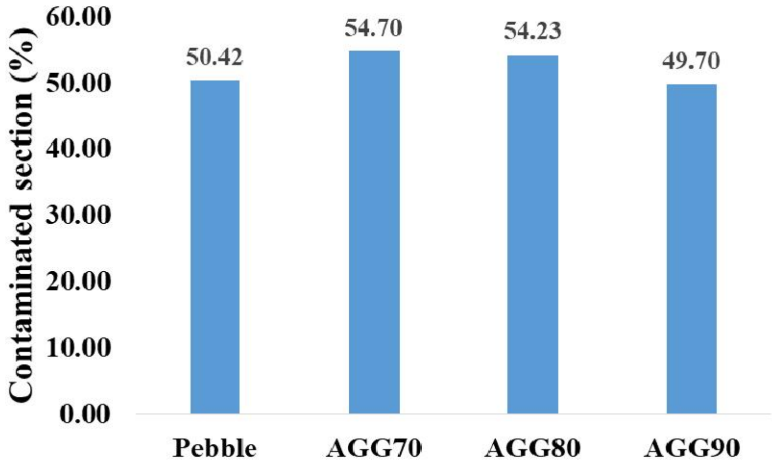

Figure 4. Chloride penetration test results after 28 days.

As illustrated in Figure 4, the samples of synthetic aggregates showed results similar to those of the pebble, with approximately 50 % of the section contaminated by the penetration of chloride ions, despite the higher water/cement ratio in the samples with synthetic aggregates. The evaluation of the resistance to penetration of chloride ions in the specimens was carried out by analyzing the area contaminated by the entry of these ions, which occurred through the diffusion process.

3.3 Structural Elements

The load application device on the beam consisted of a manually operated hydraulic cylinder with a load capacity of 1000 kN, driven by a coupled pump. Figure 5 presents an image of the beam tested. The beams have a section of 120×250 mm, a length of 1300 mm, and a span of 1100 mm. Table 2 shows the mechanical results of the beams with friezes at 30° and 45° of inclination. The test proposes to weaken the concrete section at a predefined angle, inducing its shear failure.

Table 2. Mechanical results of load, deformation and displacement of beams.

Sample	Breaking load (kN)	Deformation (%)	Displacement (mm) Limit ≤ 4.4 mm
Pebble-30	68.32	0.544	2.023
AGG80-30	81.77	0.613	3.833
Pebble-45	156.97	2.470	4.305
AGG80-45	139.12	2.338	5.281

Structures with synthetic aggregates were compared to a reference structure using natural aggregate (pebble). Parameters such as maximum load applied, deformation, and displacement were evaluated in each beam. Structural elementals with an angle of 30°, built with natural and synthetic aggregates, are called Pebble-30 and AGG80-30, respectively. Samples Pebble-45 and AGG80-45 refer to structures with a 45° angle, with natural and synthetic aggregates, respectively.

Figure 5. Beam test system.

According to the results shown in Table 2, sample AGG80-30, which uses synthetic aggregate, presented a breaking load of 81.77 kN, higher than that obtained by sample Pebble-30. In addition, the samples with a frieze at 45° demonstrated greater resistance capacity compared to the samples with a crimp at 30°. However, the reference sample Pebble-45, which uses natural aggregate, presented a breaking load of 156.97 kN, higher than that obtained by sample AGG80-45.

The deformations observed in the structures are the result of the load applied perpendicularly to the longitudinal axis of the beams. Samples Pebble-30 and AGG80-30 presented deformations of 0.544 % and 0.613 %, respectively, while samples Pebble-45 and AGG80-45 presented deformations of 2.470 % and 2.338 %, respectively. The maximum displacements obtained are within the limits established by the Brazilian standard ABNT NBR 6118:2004 [21], except for sample AGG80-45, which presented a displacement of 5.281 mm, exceeding the limit value of 4.4 mm.

Figure 6 illustrates the performance of the test on a slab produced with synthetic aggregate from bauxite residue. The punching resistance obtained for the slab was 21.80 tonnes, which complies with the acceptance criteria established by the Brazilian standard ABNT NBR 6118:2004 [21]. Based on the results obtained, the synthetic aggregate of bauxite residue proved to be suitable for application as a coarse aggregate in concrete, in addition to presenting workability conditions similar to conventional concrete for a similar dosage and under the same processing conditions.

Figure 6. Puncture resistance test.

4. Conclusions

The results of the leaching tests indicated that the concentration of sodium in the leached extract of the synthetic aggregate is low, with values lower than those established by the standard. Furthermore, the results of chloride penetration tests in concrete produced with synthetic aggregate were similar to those obtained with conventional concrete.

Tests on beams with friezes at 30° and 45° showed that the synthetic aggregate performed better than conventional concrete in terms of strength and cracking, while on beams with crimps at 45°, conventional concrete was superior. The results of the structural tests on slabs were satisfactory and in compliance with the standards.

The application of synthetic aggregate from bauxite residue in structural elements has shown promising results, reinforcing the potential of this material as a reliable and efficient alternative for use in various concrete structures. This innovation enables the responsible use of industrial waste in civil construction, contributing to the preservation of the environment and the development of more efficient and durable materials.

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