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Evaluation of the total replacement of natural coarse aggregate with mining waste coarse aggregate in the production of Portland cement structural concrete: physical and mechanical properties

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Abstract:

Background*: Following the concern of proposing solutions to minimize the environmental impacts caused by the mining industry in the state of Pará, in partnership with the company HYDRO S.A., this research was guided by the study of Fernandes, which analyzed the production stages of different types of coarse aggregates derived from bauxite, clay, and silica waste. The study utilized the coarse aggregate produced in the third production cycle, which had the highest percentage of waste in its composition, designated as AGS90.*

Materials and Methods*: This work presents an evaluation of the characterization results of the synthetic coarse aggregate (AGS) with normal specific mass compared to the natural coarse aggregate (AGN), considering their physical, chemical, and mechanical properties. Furthermore, a correlation is established between these factors and their influence on the mechanical strength and modulus of elasticity of Portland cement concrete with a normal strength class.*

Results*: Through the characterization of AGS, a disadvantage was identified, as it is still a type of aggregate with higher porosity in its structure and, consequently, greater water absorption compared to AGN. This condition negatively affected the mechanical properties of the concrete with synthetic aggregate (CAGS) up to 28 days of age. However, from the tests conducted at 91 and 277 days, an intrinsic consolidation of the composite occurred, and the results for axial compressive strength, indirect tensile strength, flexural tensile strength, and modulus of elasticity became equivalent to those of concrete with natural coarse aggregate (CAGN).*

Conclusion: *The study confirmed the technical feasibility of fully replacing natural aggregate (AGN) with synthetic aggregate (AGS) derived from bauxite waste in structural concrete of class C30. Despite the higher porosity and water absorption of AGS, the mechanical properties of the composite (CAGS) equaled those of conventional concrete (CAGN) from 91 days onward, meeting technical standards. Microstructural analysis confirmed adequate adhesion at the matrix-aggregate interface without deleterious reactions, while adjustments in binder water highlighted the need for dosage optimization. Aligning with COP30 goals, the use of AGS demonstrates sustainable potential to reduce the extraction of natural resources and repurpose mining waste. However, long-term durability studies and methods to minimize the porosity of synthetic aggregate are essential for practical applications in regions such as the Amazon.*

Key Word*: Synthetic coarse aggregate; Bauxite waste; Concrete; Testing; Microstructure; Aggregate modulus.*

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I. Introduction

The 30th United Nations Climate Change Conference (COP 30)[1], to be held in 2025 in the Brazilian Amazon Region, specifically in Belém, Pará, Brazil, is a major event dedicated to addressing global climate issues. This event has sparked initiatives within the scientific community that promote the reduction of the ecological footprint and the development of sustainable technologies. Specifically, one of these initiatives involves the replacement of natural coarse aggregates with aggregates derived from mining waste, aligning directly with this event. This study focuses on evaluating the feasibility of using a coarse aggregate produced from bauxite residue in the production of structural concrete, which is widely used in civil construction projects in the Brazilian Amazon region.

The synthetic coarse aggregate (SCA) from bauxite residue is a byproduct of bauxite ore production, which reached approximately 2.8 billion tons worldwide in 2022, with the state of Pará contributing 45% of Brazil's national production. This synthetic coarse aggregate was used as a replacement for traditional coarse aggregate, which is typically represented by crushed stone.

The extraction of natural resources leads to raw material shortages, driving the search for alternative materials, cleaner sustainability solutions, and waste recycling techniques[2]. Therefore, it is essential to seek viable and economical alternative solutions in the construction industry to mitigate the limitations of natural resources and reuse waste materials that are harmful to the environment[3].

Neville[4] highlighted that ¾ of the concrete volume is occupied by aggregates, making the quality of these materials crucial. The properties of aggregates directly affect the durability and structural performance of concrete, as well as limit the maximum strength that can be achieved in a mix. This occurs because rock fractures before visible cracks appear in the cement paste[5].

Since the synthetic coarse aggregate can be used primarily in large-scale civil construction concrete applications, this material presents a sustainable solution for managing bauxite residue, which is currently stored in containment ponds and retention systems. By recycling large amounts of this waste into coarse aggregate production, this approach reduces environmental impacts by minimizing the extraction of natural aggregate materials[6].

Currently, the Federal University of Pará (UFPA) conducts several studies in collaboration with Hydro/Alunorte to explore the application of synthetic aggregate (AGS) in construction. These studies aim to optimize the physical-mechanical and chemical properties of the material to establish it as a viable alternative to conventional aggregates, offering cost-effectiveness and environmental sustainability[7].

This research, based on the study by Fernandes et al.[8], selected the synthetic coarse aggregate with the highest percentage of bauxite residue in its composition, referred to as AGS90, from the third production cycle, for use in structural concrete with normal strength classification.

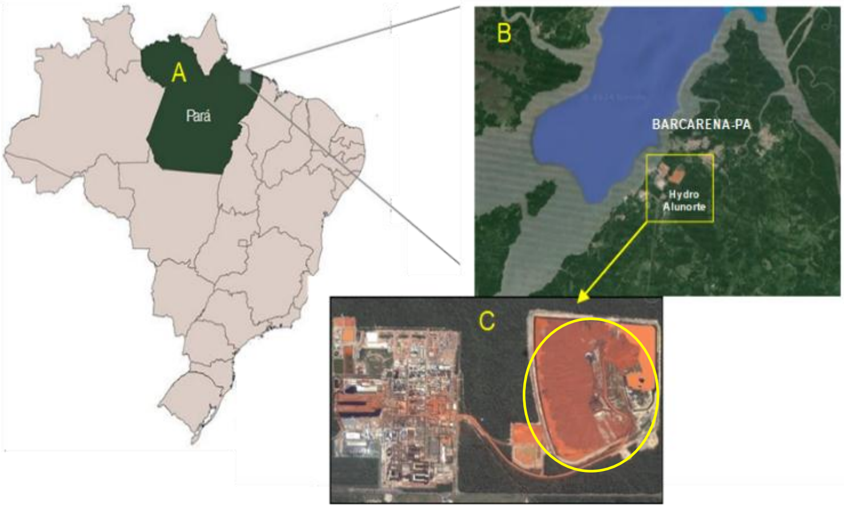
This study presents an evaluation of the characterization results of the synthetic coarse aggregate (AGS) with normal specific mass, compared to natural coarse aggregate (NCA), in terms of their physical, chemical, and mechanical properties. The influence of these aggregates on mechanical strength and elastic modulus in Portland cement concrete of normal strength classification is analyzed. Specifically, the research also provides comparative results between synthetic coarse aggregate concrete from bauxite residue (CAGS) and natural coarse aggregate concrete (CAGN).

The study evaluates these concretes in both their fresh state (analyzing workability, bulk density, and cement consumption) and their hardened state (examining water absorption, porosity, specific mass, static elastic modulus, fracture behavior, compressive strength, splitting tensile strength, flexural strength, and matrix-aggregate interface through scanning electron microscopy (SEM)).

II. Material And Methods

Bauxite residue (BR), formerly known as red mud, originates from the bauxite beneficiation process, known as the Bayer process[8]. These BR deposits are classified as solid waste deposits (SWD), and the Hydro Alunorte refinery, located in the state of Pará, has storage facilities with a capacity of 92.2 Mm³ (million cubic meters) (Figure 1).

Figure 1: Location of the bauxite residue study area. A and B) Factory site (Google Maps, 2025) C) Residue storage area managed by HYDRO-ALUNORTE in Barcarena – PA[6]. Adapted. Authors, 2025.

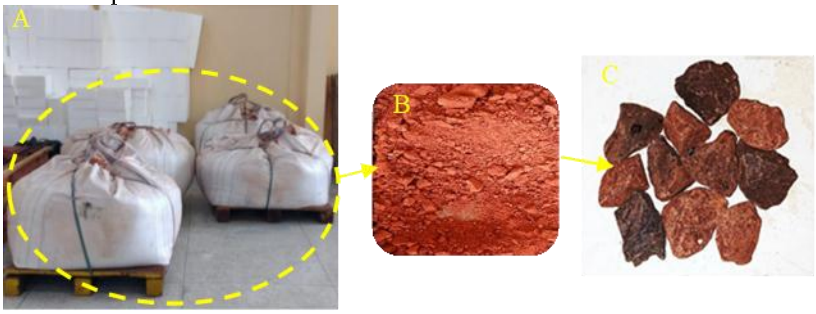


Materials

Bauxite Residue

Fernandes et al.[8] emphasize that the production of synthetic coarse aggregate was achieved through the use of raw materials: kaolinite clay, silica, and bauxite residue (BR) supplied by the company HYDRO-ALUNORTE in Barcarena-PA and stored at the Civil Engineering Laboratory of UFPA, as shown in Figure 2.

Figure 2: Storage of bauxite residue in the Civil Engineering Laboratory of UFPA. A) Arrangement of the material as it was transported and subsequently stored, B) Appearance of the raw residue, and C) Sample of the produced SCA. Source: Adapted from Fernandes et al[8].



Aggregates

The fine aggregate is natural sand from a quartz riverbed in the Amazon region, near the municipality of Ourém, in the state of Pará. Only physical characterization tests were conducted on this material, yielding results of a specific gravity of 2.62 g/cm^3, a unit weight of 1.61 g/cm^3, and a water absorption of 1.5%. Through the granulometric analysis, a fineness modulus of 2.4 and a maximum particle size of 1.18 mm were obtained, classifying it as medium sand.

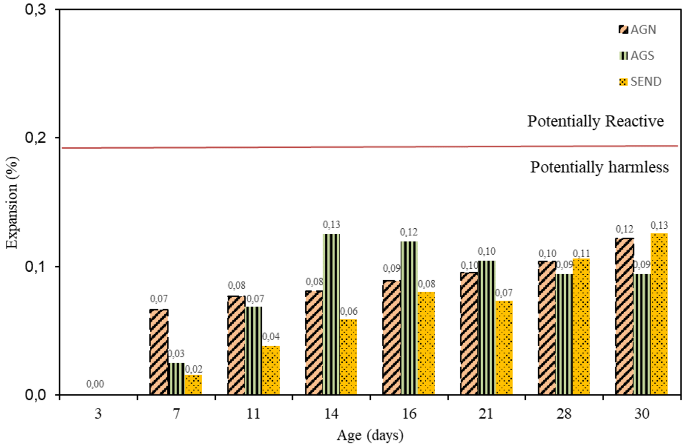
The natural coarse aggregate used was river gravel (NCA) sourced from riverbeds in the city of Ourém, PA, and purchased from a construction materials store in the Metropolitan Region of Belém, PA. Physical characterization tests were also conducted on this material, resulting in a specific gravity of 2.6 g/cm^3, a unit weight of 1.61 g/cm^3, a water absorption of 1.97%, a shape index of 2.01, and a fineness modulus of 2.3. The maximum particle size was 19.0 mm, classifying it as medium gravel or No. 1 gravel.

However, another coarse aggregate used in this research was a synthetic type produced at a temperature of 1250°C, referred to as third-cycle SCA, with a higher percentage of bauxite residue in its composition. It was supplied by the company HYDRO ALUNORTE and produced in the chemical engineering laboratory of the Federal University of Pará, as described by Fernandes et al.[8]. Physical characterization tests were also performed on this type of aggregate, yielding results of a maximum diameter of 19.0 mm, a fineness modulus of 1.84, a shape index of 1.99, and a water absorption of 3.20%.

Specifically, only the coarse aggregates underwent mechanical characterization through the Los Angeles abrasion test. The results were 52% for NCA and 27.41% for SCA, demonstrating that only the synthetic aggregate is suitable for use in structural concrete mix design, in accordance with NBR 7211[9]:2022[3]. In contrast, the natural aggregate is considered friable and is not recommended for use in structural concrete.

Considering the importance of investigating aggregate durability and verifying whether they are inert when in contact with cement alkalis, alkali-aggregate reaction tests were conducted on the fine aggregate (sand) and the coarse aggregates, both natural (gravel) and synthetic (SCA), as shown in Figure 3.

Figure 3: Results of alkali-aggregate reaction tests for sand, NCA, and SCA according to NBR 15577-4.



Since SCA is produced from a mining residue (bauxite) in a laboratory-controlled process and has not yet been used in direct exposure conditions to sulfate, Fernandes et al[8], conducted a durability evaluation test using sodium sulfate solutions (DNIT 446/2024-ME)[10] for this aggregate. The results showed only minor disintegration of the aggregate, with a mass loss of less than 0.1%, thus meeting the maximum allowable limits for this durability test, in accordance with DNER 037/1997-ME[11].

Portland Cement

The cement used throughout the research is the Brazilian Portland CP II F32 type, consisting of 75-89% by mass of clinker and calcium sulfate, and 11-25% carbonate material, according to NBR 16697:2018[12]. It has a specific gravity of 2.85 g/cm^3. This type of cement was chosen for the study due to its common use in construction projects in the Amazon region.

Production of Specimens from AGS

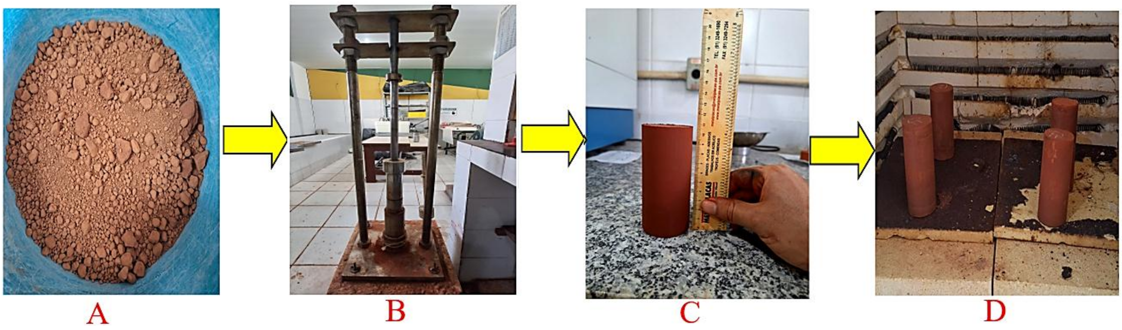
Uniquely, specimens were produced using the same materials and the same proportional mixture percentages required for the production of AGS90.

The methodology applied for the preparation of the specimens was based on the recommendations of NBR 7182[13]. A total of nine specimens were produced, with three units designated for each of the following tests: specific mass, absorption, and void index determination, in accordance with NBR 13278[14] Figure 5 illustrates the axial compression tests performed according to NBR 5739:2018[15], the static deformation modulus test following NBR 10341[16] and the dynamic deformation modulus test, as recommended by NBR 8802:2019[17]. All specimens were stored in a controlled environment.

The specimen preparation process involved filling three metallic cylinders, each with a height of 10 cm and a diameter of 5 cm. The material was homogenized for 10 minutes, following the guidelines of NBR 7182:2025[13]. Three layers of material were placed in the molds, and each layer was compacted using a manual tamper, applying 26 blows at distinct points.

Afterwards, the samples underwent a sintering process in furnaces for three hours at a temperature of 1250°C. Once sintered, the samples were cooled and demolded. Figure 4 shows the specimen production process.

Figure 4: Simplified process of producing AGS specimens. A) Raw bauxite residue. B) Specimen molding. C) Molded specimen before sintering. D) Molded specimen after sintering.

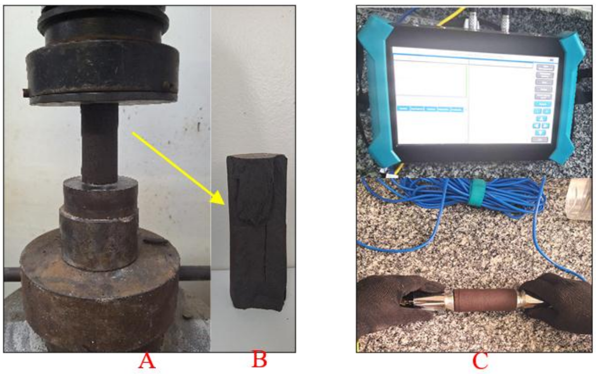


The mixing process is demonstrated in the work of Fernandes et al[8] for the production of synthetic coarse aggregate. However, it is important to emphasize that the processes are similar only in the mixing stage. For the production of the specimens, the methodology described in NBR 7182[13] was followed.

Figure 4 a shows well-formed specimens with dimensions of 50 mm in diameter and 100 mm in length, before being placed in the muffle furnace for sintering at a temperature of 1250°C. After three hours at this temperature, the samples underwent a natural cooling process in a laboratory environment. It is observed in Figure C that after sintering, the samples experienced slight deformations and volume reduction. This situation was expected; however, since this is a pilot study, the extent of deformation was unknown. Therefore, this production stage will be better evaluated in future research.

After the AGS specimen production was completed, the mechanical properties were evaluated through the axial compression test[13] and the dynamic modulus of elasticity test (ASTM C597-16[17]), using the ultrasonic pulse velocity test[18] (Figure 4.C). Figures 5.A and 4.B show the AGS specimen during the compression test and the fracture after failure.

Figure 4: Mechanical Strength Tests of AGS Specimens. A) Axial compression test. B) Fractured specimen. C) Dynamic modulus of elasticity test.



Mix Proportioning and Preparation of Unit Mix Designs

NBR 6118:2023[18] establishes that concrete structures must be designed and constructed so that, under the expected environmental conditions at the time of design and during use, they ensure safety, stability, and serviceability throughout their intended service life.

This research was based on the recommendations of NBR 12655[20] for concrete production, adopting Aggressiveness Class II, concrete classification according to NBR 8953[21] (CA ≥ C30), and ensuring a Portland cement consumption per cubic meter of concrete of at least 280 kg/m³. Thus, a concrete mix with a characteristic compressive strength of 30 MPa at 28 days was obtained, based on the mix design diagram using the IBRACON method.

It is important to emphasize that no additives were used in the AGS concrete mix to better assess the influence of the porosity of this type of aggregate, given that it has an absorption rate greater than 2%. The concrete production took place in a controlled laboratory environment at the Civil Engineering Department of UFPA, aiming to minimize standard deviation (Sd) variations as much as possible.

Table 1: Compressive Strength Results for Mix Design Curve Development.

Strength (Mix - MPa)		Average Fckj (28 days)	Standard Deviation (Sd)
CAGN	Rich	34,91	0,01
	Normal	29,97	0,03
	Lean	20,34	0,05
CAGS	Rich	29,41	2,23
	Normal	20,10	3,98
	Lean	12,79	0,28

The experimental mix designs obtained from the dosage curves required adjustments to the water/cement ratio during dosing through the slump test[22] to maintain consistency within the designated class. The concretes CAGN and CAGS were evaluated in their hardened state through mechanical tests, including simple axial compression at the ages of 7, 28, 91, and 277 days on cylindrical specimens (100x200 mm), split tensile strength, and flexural strength at 28 days on cylindrical specimens (100x200 mm) and prismatic specimens (150x150x500 mm). The static modulus of elasticity was assessed at 28 and 91 days on cylindrical specimens (100x200 mm), with three replicas per test. Additionally, the concretes were analyzed through water absorption and void index tests to establish correlations with mechanical strength.

Table 2 summarizes the properties of the cementitious composites produced with AGN, referred to as CAGN, and those produced with AGS, referred to as CAGS. Due to the requirement that the experimental concrete mixes maintain the same consistency range determined by the dosage curves, the mixing water used for CAGN was lower than initially planned, whereas CAGS required a higher water content. These adjustments directly influenced the final binder water ratio of the composites and their respective mechanical properties.

Table 2: Mix design for the composites studied.

Composite/ aggregate type	Mortar content (%)	Unit mixture	Water/cement binder (initial)	Water/cement binder (final)	Slump test (mm)	Cement (kg/m³)	Moisture content (%)	Fresh concrete µ (Kg/m³)
CAGN	55	1:2,03:2,48	0.55	0.52	90	380	9,40	2380,96
CAGS	55	1:1,42:1,98	0.51	0,61	52	370	13,84	2336,39

The concrete slump was set between 50 mm and 100 mm, in accordance with resistance class S-50[23]. The axial compressive strength in this study was defined as 30 MPa, as it corresponds to class C30[24], a type of concrete commonly used in vertical construction projects. The concrete mixing process was conducted at the Civil Engineering Laboratory of the Federal University of Pará in Belém, Pará, Brazil.

III. Result and Discussion

Influence of the Mechanical Properties of Coarse Aggregates on the Axial Compressive Strength and Modulus of Elasticity of Concretes

As previously demonstrated, specimens of AGS were produced for physical tests, including water absorption, porosity, apparent specific gravity, and mechanical strength and modulus of elasticity tests. Table 3 presents a summary of the results of the physical and mechanical tests, while Figures 10 and 11 show a comparison between the axial compressive strengths and moduli of the coarse aggregates with the composites.

Table 3: Results of the Characterization Tests and Mechanical Strengths of AGS Specimens.

Aggregate type	Dimensão DxL (mm)	Absorção (%)	Void Index	Specific Gravity (g/cm³)	fc (MPa)	Ed (GPa)
CAGS	47 x 97	1,89	3,65	1,93	55,79	18,68

Figure 5: Mechanical Strength of Coarse Aggregates and Composites at 28 Days. A) Axial Compression. B) Modulus of Elasticity.

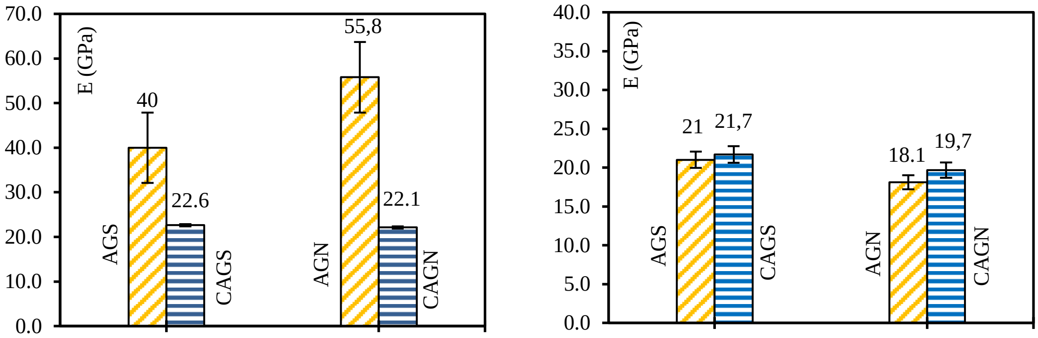


Figure 5A presents a comparative graph of the axial compressive strength of natural and synthetic coarse aggregates against the strengths of the composites. It is worth noting that only the synthetic aggregate was tested through mechanical testing, while the strength of the rolled gravel was estimated based on the literature. According to Neville[6] aggregates exhibit significantly higher strengths than the cement paste itself and also report that when an aggregate has good quality, its increased proportion in the mix design enhances the strength of the concrete. This assertion aligns with the results obtained, as despite the natural coarse aggregate having a higher strength than the synthetic one, the strengths of the concretes were similar. Thus, it is understood that the failure occurred significantly in the paste.

Figure 5B shows comparative results between the modulus of elasticity of coarse aggregates and the strengths of the composites. It should also be emphasized that only the synthetic aggregate was tested through mechanical testing. For the rolled gravel, the study by Mehta[23] was followed, in which tests conducted with samples of sandstones, limestones, and porous gravels indicated moduli ranging from 21 to 49 GPa. The modulus of elasticity of gravel, being generally composed of minerals such as quartz and feldspar, can be around 40-70 GPa. For this research, a value of 30 GPa was adopted for the modulus of the rolled gravel used in the study, corresponding to the value found in the dynamic modulus of elasticity test of the synthetic coarse aggregate, which was 29.59 GPa. This correlation is based on the results obtained from the static modulus of elasticity tests of the studied concretes, which were 18.63 GPa and 19.69 GPa for CAGN and CAGS, respectively.

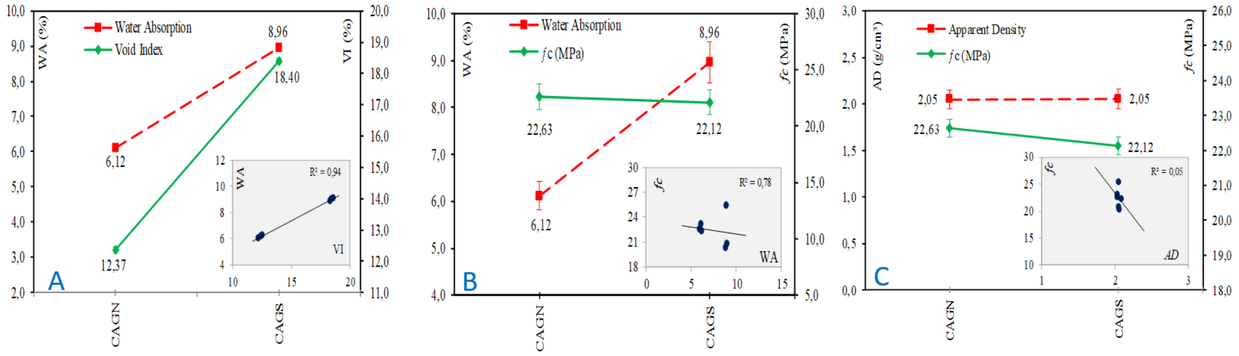
Although the synthetic coarse aggregate has a higher porosity than the natural coarse aggregate, which is a significant characteristic that determines its stiffness and directly affects the modulus of elasticity of the concrete, no impairment in the stiffness of the concrete was observed, resulting in no significant difference between the moduli of elasticity of the studied concretes.

Influence of the Physical Properties of Concrete on the Axial Compressive Strength of Concretes

Figure 6A shows the graph of the relationship between water absorption and void index in the concretes of this study. In this context, when observing only the spectrum of concrete porosity, CAGN performs better than CAGS and will yield better results concerning the physical durability properties of the concrete.

It is important to note that CAGS is more porous due to the increased water in the unit mix for correcting the binder water adjusted in the slump test. Additionally, this condition is attributed to the porosity of AGS. According to Rossignolo[24], a high percentage of water absorption in the aggregate can cause damage to the concrete in its hardened state, such as drying shrinkage, increased specific gravity, and reduced fire resistance. However, there are also some benefits derived from a high water absorption capacity of the aggregate, such as improving the properties of the transition zone between the aggregate and the cement paste, thereby reducing the "wall effect." Moreover, the water absorbed by the aggregate benefits the internal curing of the concrete.

Figure 6: Physical Properties of the Studied Concretes. A) Void Index vs. Absorption. B) Apparent Density vs. Compressive Strength. C) Absorption vs. Compressive Strength.



Panel A shows the directly proportional relationship between water absorption and the porosity of the composites CAGS and CAGN. The other results obtained from graphs B and C relate the apparent specific gravities and porosities found in these composites to the compressive strengths at 28 days.

It is established that the relationship between specific gravity and porosity is inversely proportional and that factors such as the porosity of coarse aggregates can affect the rheological and mechanical properties and the modulus of elasticity of concrete. Thus, it can be observed from the graph that the water absorption of CAGS is 46% higher than that of CAGN. This condition did not create a difference in the results found for the apparent specific gravity of the composites, as shown in the panel. However, when observing the compressive strength at 28 days, even though CAGS is more porous and has a higher percentage of water absorption, it exhibits a higher strength by approximately 9%. This indicates that factors of porosity and water absorption, when analyzed in isolation, do not significantly influence the axial compression of the composites in this research.

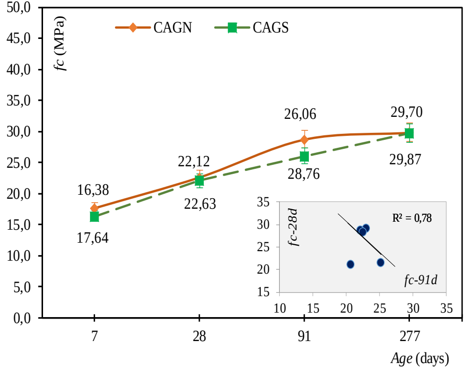
Analysis of Axial Compressive Strength and Modulus of Elasticity at Different Ages of Concretes

Compressive strength is considered by many to be the fundamental technological control in concrete, often overshadowing other tests that may require greater attention from the designer[6]. The compressive strength of concrete serves as an indirect assessment for determining other properties of the material. However, there may often be simplifications that do not accurately characterize certain characteristics, which is why a deeper understanding of these properties, such as the modulus of elasticity, becomes essential[7] .

Through a systematic analysis of the literature, it was possible to verify that there are several studies related to concrete with coarse aggregate made from bauxite residue. Although these studies are still in their infancy, the results presented are promising, particularly the works of Souza[25], Junior et al[26] and Santos et al[27], which produced concrete that achieved a maximum axial compressive strength of 40.34 MPa. This demonstrates that concrete with synthetic coarse aggregate has the potential to reach high compressive strengths.

As a new material, efforts are still being made to consolidate results through mitigating processes of reproducibility/repeatability, and to evaluate the physical, chemical, and mechanical applicability/viability over the long term in structural concrete, in this case, of normal strength. This study evaluated the axial compressive strength at ages of 7, 28, 91, and 277 days to determine the contribution of AGS to this mechanical property at both early and advanced ages.

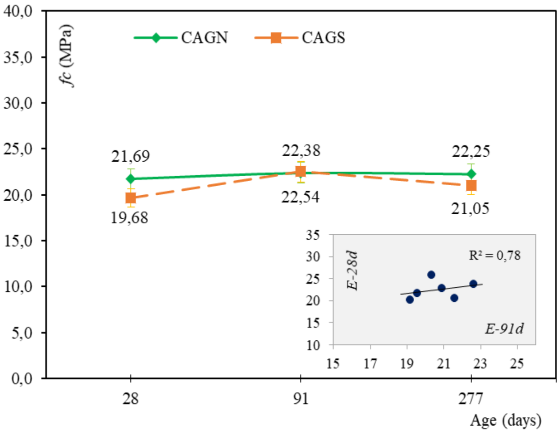
Figure 7: Graph of the Mapping of Axial Compressive Strength of Composites CAGN and CAGS at Ages 7, 28, 91, and 277 Days.



The compressive strength graph shows that both composites experienced a significant increase in strength up to ages greater than 91 days. The results also indicated that both CAGN and CAGS achieved very similar strength values. However, when related to the experimental mix derived from the dosage curve for the age of 28 days, estimated at 30 MPa, the produced batch of specimens initially would not meet the pre-established strength requirement but would still comply with the requirements established in NBR 12655[20] concerning aggressiveness class.

A more critical analysis of the calibration of the equipment used to conduct the modulus of elasticity tests on concrete is rarely addressed in the literature. However, one cannot overlook the importance of this calibration in obtaining reliable results[26]. NBR 6118[19] states that the elastic deformation of concrete depends on the composition of the concrete mix, especially the nature of the aggregates. Mehta and Monteiro[23] emphasize that the modulus of elasticity and the compressive strength of concrete are two properties that do not evolve in the same manner over time[7] . Based on this assertion, this research did not limit its evaluation of the modulus at the prescribed age of 28 days but extended the analysis to other ages, similar to that done for axial compression at more advanced ages of 91 and 277 days, as demonstrated in Figure 15. At 28 days, the modulus of CAGN was about 15% higher than that of CAGS, but at 91 days, this difference was less than 1%. The test conducted at 277 days confirms, based on the results obtained, that there was an intrinsic consolidation of the microstructure of both composites due to the small variation in their respective moduli.

Figure 8: Graph of the Mapping of the Modulus of Elasticity of Composites CAGN and CAGS at Ages 28, 91, and 277 Days.



The results were considered satisfactory for CAGS, taking into account the considerations highlighted by Rossignolo[24], who stated that for concretes with normal specific gravity and axial compressive strength values ranging from 20 to 50 MPa, the modulus of deformation can typically vary between 50% and 80% of the obtained value.

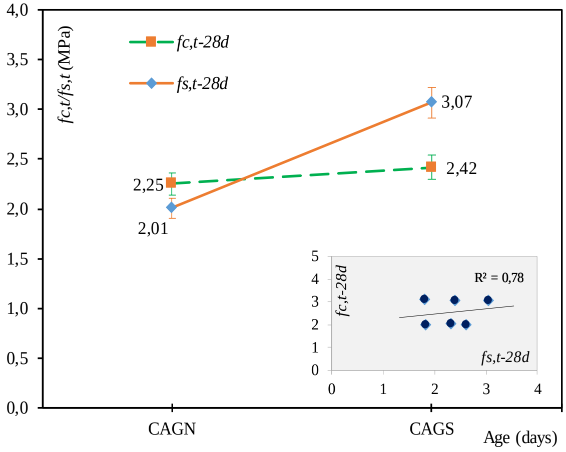
In item 8.2.8 of NBR 6118[19] it is described that the modulus of elasticity (Eci) should be obtained according to the testing method established in ABNT NBR 8522, with this standard considering the initial tangent modulus obtained at 28 days of age. Additionally, if it is not possible to perform the tests, the initial modulus of elasticity can be estimated using the expression: $Eci = \alpha E.\sqrt{fc}$, for concretes with $f$ck ≤ 50 MPa. Following this calculation methodology, values of α e were determined to be 0.9 for the rolled gravel AGN used in CAGN, the same value adopted for limestone as stated in this standard, and 1.34 for the coarse aggregate of bauxite residue (AGS) used in CAGS, which is greater than the value adopted for basalt and diabase.

Since the static modulus of elasticity test of the concretes was stipulated for compression stresses less than 0.5 fc and tensile stresses less than $f$ct, the Poisson's ratio (ν) can be taken as equal to 0.2, as stated in item 8.2.9 of NBR 6118[19].

Comparative Analysis of the Results of Split Tensile Strength and Flexural Strength

When analyzing the graph of indirect tensile strength and simple flexural strength[28,29,30], as demonstrated in Figure 16, and making an analogy with the results obtained for axial compression at 28 days, there is an approximate variation of 10-11% related to indirect tensile strength and 9-14% related to simple flexural strength. These results are within the normative parameters for normal strength concretes and align with the systematic review[27] referencing the results of split tensile strength from the works of Rosário[31] and Souza[25], which addressed this topic related to normal strength concrete produced with coarse aggregate made from bauxite residue, with results ranging from 2.36 MPa to 3.29 MPa, respectively, thereby confirming a direct correlation with the strengths obtained in axial compression.

Figure 9: Graph Showing the Relationship in Tensile and Flexural Strength of Composites CAGN and CAGS at 28 Days.

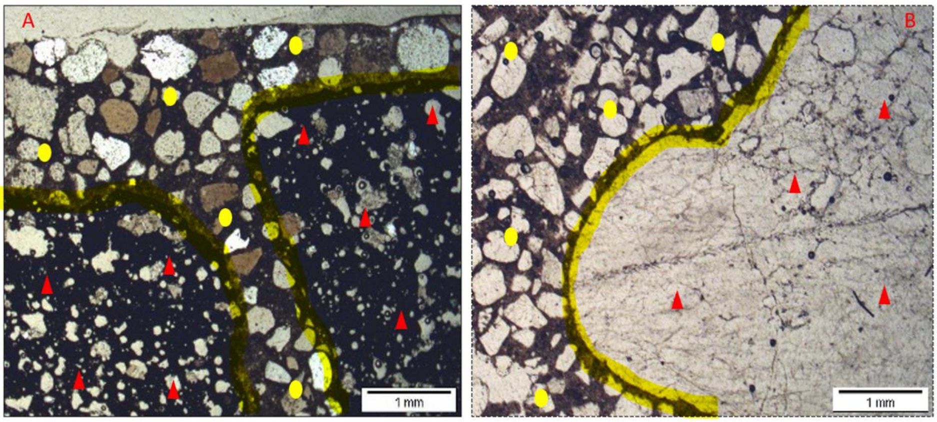


Analysis of the Microstructure of Fractured Concrete Using Optical and Scanning Electron Microscopy (SEM)

In order to analyze the microstructure of the matrices and transition zones of concretes with synthetic and natural coarse aggregates, images were obtained using an optical microscope (Figure 17) and a scanning electron microscope (SEM) (Figures 19 and 20) from samples of fractured concrete specimens tested for split tensile strength at 28 days. The sample preparation involved fragmenting the samples into convenient sizes, followed by drying them in an oven at 100°C for a period of 24 hours, and finally polishing them into thin sections.

Figure 10: Image Obtained Through an Optical Microscope of the Microstructure of the Transition Zone of the Composite. A) Polarized Light - CAGS. B) Natural Light - CAGN.

Legend: 🟨 Delimitation of the transition zone. ▲ Coarse Aggregate (dispersed phase). ● Mortar (cementitious matrix).



Isaia et al [33] define the contact zone as the relationship between the grains of coarse and fine aggregates that merge with the cement paste, surrounding and separating the aggregates, generating films of water around the grains and forming a weaker layer at the interface. Neville[6] concludes that this transition zone has higher porosity and, therefore, lower strength.

The SEM analyses were performed using the LS15 EVO model microscope from Zeiss at LAMIN-BE. The samples were metalized with a thin layer of gold to obtain backscattered electron (BSE) images.

Figure 11: mages Obtained by Scanning Electron Microscopy (SEM) of the CAGS Sample. A) Visualization of the Microstructure. B) Detail of the Zone.

Legend: 🟨Delimitation of the Transition Zone 🟩Cracks ▲ Coarse Aggregate (impregnated with refractory material).● Porosity in the Coarse Aggregate and Cementitious Mortar.

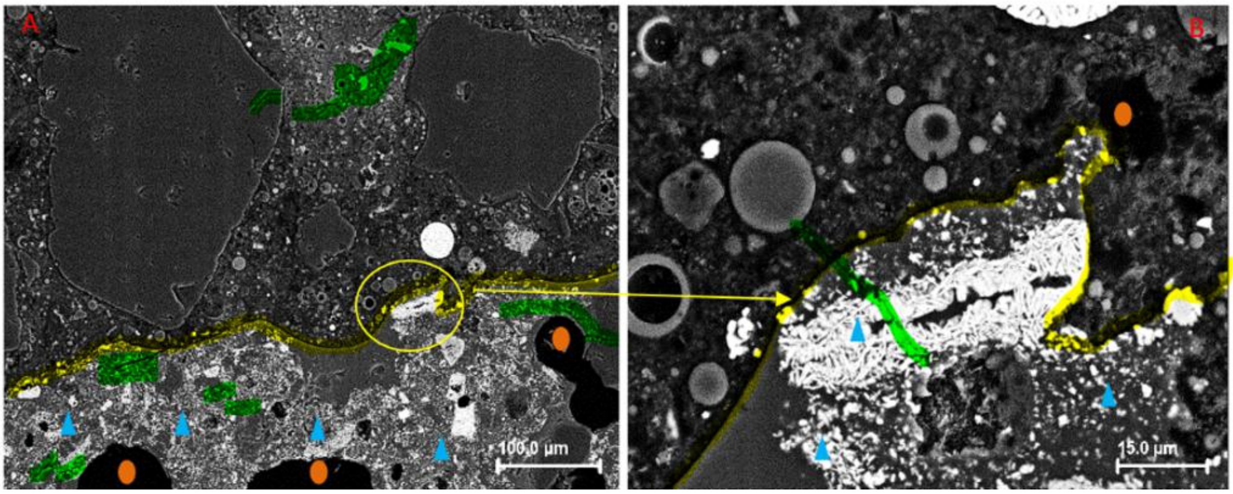
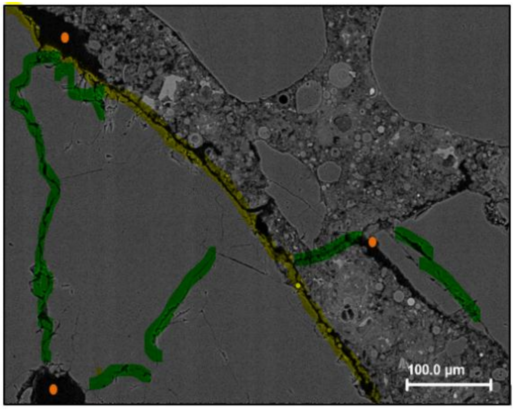


Figure 12: Images Obtained by Scanning Electron Microscopy (SEM) of the CAGN Sample.
Source: (Authors, 2024).

Legend: 🟨Delimitation of the Transition Zone. 🟩Cracks. ● Porosity in the Coarse Aggregate and Cementitious Mortar.



The analyses of the fractured concretes using the optical microscope involved visualizing the surfaces of the mortars and coarse aggregates, as well as the interface of the transition zone. Figure 17 highlights the clear separation through the transition zone between the cementitious matrix of the composites with the dispersed phase and the coarse aggregates. Figure 17.A also shows a detail of the synthetic coarse aggregate concerning the distribution of silica grains, represented by the white dots in the bauxite residue, covering the entire dark area.

Through the use of SEM, it was possible to verify in Figures 18 and 19 the delimitation of the matrix and dispersed phases through the zones of the CAGN and CAGS composites, as well as the existing cracks and pores. Another important aspect to highlight in Figures 18.A and 18.B, in the region where the AGS is located, is the high concentration of whitish flakes. This situation arises, as explained in the work of Fernandes et al.[8], because during the production of the synthetic coarse aggregate, in the sintering stage in an electric furnace at a temperature of 1250°C, there is often detachment of refractory material used on the internal walls, resulting in the impregnation of various produced aggregate stones. Subsequently, during the production of the CAGS composite, scraping was performed on the stones that contained impregnation of refractory material. However, in some stones, complete scraping could not be achieved. Nevertheless, it is important to note that this situation does not cause reactions with the alkalis in the cement or lead to a loss of mechanical strength of the AGS.

Both the CAGS and CAGN samples exhibited fractures in the cementitious matrix, which is documented in the specific literature for normal strength concrete. However, it is observed in Figure 19 that

CAGN exhibited greater quantities and thicknesses of shear cracks compared to CAGS, as shown in Figure 18. This type of crack is not expected in coarse aggregates present in normal strength concrete. However, it corroborates the results obtained earlier in the Los Angeles abrasion test, where AGN was identified as a friable coarse aggregate.

Figure 19 shows a higher quantity of pores in the synthetic coarse aggregate, which is a factor that contributed to the mixing water absorption, thus increasing the final binder water ratio and consequently decreasing the mechanical strength. It was also observed that there is good adhesion between the mortar and CAGS in the transition zone.

IV. Conclusion

Influence of AGS Quality on the CAGS Composite

The consistency and axial compressive strength are concrete properties influenced by the physical, chemical, and mechanical characteristics of aggregates. In this research, the synthetic coarse aggregate used had the highest proportion of bauxite waste in its composition, as reported in the study by Fernandes et al. (2025). The results demonstrated that, concerning physical characteristics—such as grain shape, particle size distribution, and maximum aggregate size—it was possible to adjust the classification in accordance with the requirements of NBR 7211, 2022, allowing for proper concrete mix design.

On the other hand, this aggregate still has higher porosity compared to natural coarse aggregate, specifically river gravel, which was used in this study as a benchmark. This resulted in a concrete with greater porosity compared to the reference concrete.

Based on the findings of Fernandes regarding aggregate wear due to the Los Angeles abrasion test, alkali-aggregate reaction, and sulfate attack resistance, the results were considered satisfactory, as they met the requirements of NBR 7211. Correlating these findings with the microstructural analysis of the studied concrete, no deleterious anomalies were observed up to 277 days of age.

Influence of AGS Porosity on the Binder Water of CAGS

Given that the synthetic coarse aggregate has a porosity level that is not ideal due to its laboratory-based production process, it results in higher water absorption compared to natural coarse aggregate. This condition altered the binder water content of the concrete, increasing it from 0.51 to 0.61 in the final corrected mix design. This adjustment was necessary because the synthetic coarse aggregate absorbed a portion of the water that was intended exclusively for cement matrix hydration. Consequently, additional water was used in the mix to adjust the concrete consistency.

This increase in binder water to maintain consistent workability affected the results of axial compressive and tensile strength, as well as the modulus of elasticity, up to 28 days of age.

Influence of Axial Compression and Modulus of Elasticity of AGS on the Mechanical Properties of CAGS

This study evaluated axial compressive strength at 7, 28, 91, and 277 days to determine the contribution of AGS to this mechanical property at both early and advanced ages. AGS contributed positively since it was not considered friable, as indicated by the abrasion test results, and because it had a compressive strength above 50 MPa, which is greater than that of the cementitious matrix.

The results obtained from compression and flexural tensile strength tests were within the standard parameters for normal-strength concrete, according to NBR 6118, 2023, supporting the systematic review conducted.

From the evaluation of the modulus of elasticity of concrete with AGS at 28, 91, and 277 days, it was concluded that the synthetic coarse aggregate contributed effectively to the intrinsic consolidation of the microstructure from 91 days onward. This was due to the aggregate’s porosity and the gradual release of absorbed water back into the cementitious matrix over time.

A particularly important and unprecedented criterion, based on the calculation methodology outlined in item 8.2.8 of NBR 6118, 2023, combined with the static modulus of elasticity results for CAGS at 28 days, allowed the determination of the α e value for the synthetic coarse aggregate as 1.4. This value can be used as a theoretical reference for estimating the modulus of elasticity of normal-strength concrete containing this type of synthetic coarse aggregate.

CAGS Microstructure

Optical and scanning electron microscope (SEM) images revealed a well-defined transition zone between the cementitious matrix and the synthetic coarse aggregate grains. Additionally, most fractures were observed in the cementitious matrix, a situation predicted in the literature for normal-strength concrete.

No ruptures were observed in the synthetic coarse aggregate, only minor shear cracks, which were significantly fewer than those found in the natural coarse aggregate. This finding is consistent with the results of the Los Angeles abrasion test, in which the synthetic coarse aggregate exhibited less mass loss, while the natural coarse aggregate was classified as friable.

SEM microstructural images of the concrete also revealed a greater number of pores in the synthetic coarse aggregate, which contributed to the absorption of mixing water, leading to an increase in the final binder water ratio and, consequently, a reduction in mechanical strength.

Final Considerations

One aspect observed in the characterization of the synthetic coarse aggregate was its limited contribution to the mechanical properties of concrete. The aggregate's porosity led to higher water absorption and increased voids in the concrete compared to concrete with natural coarse aggregate.

Another noteworthy point is that, as this is a novel material still undergoing research, further studies are needed to consolidate results based on mitigating processes for reproducibility/repeatability and to evaluate its long-term physical, chemical, and mechanical applicability and feasibility in normal-strength structural concrete.

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