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Improving the Mechanical Properties of Concrete by Adding Recycled Aggregate

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***Abstract*— Construction industry is a major source of environmental impact, both in terms of the large volume of construction waste generated by building or demolition work, and in terms of the number of natural resources taken from the environment. The production of concrete consumes large quantities of natural resources such as sand, gravel, lime, and drinking water. The reuse of waste generated by the construction industry can generate new possibilities for the market, thus opening a new path for the sustainable use of natural resources, ensuring that waste is nobly reinserted into the production chain. This research evaluated the influence of the addition of Recycled Concrete Aggregates (RCA) on axial compressive strength, flexural tensile strength and diametrical compressive strength. The study presents the results of the granulometric and physical characteristics of Recycled Concrete Aggregate obtained from a precast concrete company in the state of São Paulo in Brazil. The concretes were prepared with proportions of 25%, 50% and 100% of Recycled Concrete Aggregate (RCA) as a substitute for natural crushed aggregate. The influence of the recycled aggregate on the concrete in its fresh state (workability) was initially evaluated, followed by its hardened state (axial compressive strength and flexural tensile strength). According to the results presented in the research, there is great potential in using recycled concrete aggregates to replace natural aggregate, with a focus on the precast industry, if prior studies of the waste are carried out and its shortcomings are taken into account in calculations.**

***Keywords*—waste; recycled; aggregate; concrete; mechanical strength.**

I. INTRODUCTION

Concrete is the most widely used construction material in the world, second only to water [1]. According to the Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE), in 2019 approximately 56% of the waste generated in Brazil came from construction and demolition activities, which is equivalent to approximately 44.5 million tons of MSW generated per year, out of a total of 79 million tons of municipal solid waste.

In Brazil, 142,738 tons of MSW are collected per day, with a per capita average of 0.68 kg/inhabitant/day [2]. However, the data provided by ABRELPE refers to the amount collected by municipalities, considering only what has been abandoned on public roads and streets.

To minimize environmental impacts, as well as social and financial ones, the solution is to use recycled materials, since recycling reduces the extraction of natural resources and energy consumption, developing an activity with less production and inadequate waste disposal [3].

In the construction sector, concrete can be found in many buildings and works of art. It is widely used throughout the world due to its ease of application, low cost and durability. Concrete is an artificial stone that is shaped by human ingenuity [1].

Concrete's basic structure uses a binder, fine aggregate, coarse aggregate and water. Concrete consumes 80% of the aggregates market for its production alone [4]. The coarse and fine aggregates in concrete are primarily of natural origin and, with the increase in waste generation, it is necessary to consider the use of recycled aggregates to reduce the environmental impact caused by their own waste and the extraction of natural aggregate [5].

The use of concrete rejects can generate various possibilities for the market and its supply chain, opening possibilities such as the implementation of reverse logistics which becomes more effective, guaranteeing a more noble destination for the reject, reinserting it into the production chain. In the case of recycled aggregate, [6; 7] states that there could be significant savings for the market if it can be introduced into the production of new concrete.

However, [8] restricts the use of concrete with recycled aggregate only to the non-structural field and low strength classes and imposes tests for its use. The standard claims that there is a need for further studies of this type of concrete, so that it can be widely used in structural works, and states that there is a need to create a new standard.

There is the possibility, then, of carrying out studies into the applicability of this material in reverse, in the manufacture of new concretes, but there has been little study into the use of this material in structural elements [9].

In their study [10], construction waste is a potential source of aggregates, through Concrete Waste Aggregate (CWA) to produce new concretes.

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As recycled concrete aggregates (RCA) have residual mortar adhered to their surface, they are more porous, have a lower specific density and a greater capacity to absorb water, thus presenting lower physical and mechanical properties when compared to natural aggregates (AN) [11].

Care should be taken when determining the specific mass of aggregates [12], as they contain pores, both impermeable and permeable, which can give false results in tests. In his tests, Leite [10] found the specific mass of RCA to be 30% lower than natural ARC, while [13] obtained values between 12 and 18% lower. This characteristic was also noted in the study by [14], who stated that RCA concretes have a lower density than conventional concretes, although this characteristic can be used to produce lightweight concretes.

In relation to particle size, [13] states that it is not directly responsible for the final strength of a concrete with a defined water/cement ratio and fully compacted; particle size is responsible for ensuring the workability of the concrete.

In his study, [15] compares the granulometry of ARC with granite gravel 0 and concludes that RCA has a coarse granulometry than the control material, with an average diameter of 8 mm compared to 6 mm for natural aggregate, and that the means of obtaining RCA is a primary factor in defining its granulometry. For [6], RCA is like crushed rock and the equipment used to crush it directly influences its gradation.

Concrete made with recycled aggregate suffers from workability problems due to its more porous texture and high absorption rate [9]. Lower workability leads to the use of more water and additives to ensure that this property is maintained. This changes the water/cement ratio and, consequently, the mechanical properties of the concrete in the hardened state.

Concrete mixtures with recycled aggregate produce concretes with lower workability due to the shape and porosity of the recycled aggregate. In this way, concrete with recycled aggregate requires more water to guarantee the same workability as conventional concrete [16].

Regarding compressive strength [17], different types of coarse aggregates can result in concretes with different strengths using the same quality of mortar. This reiterates the importance of studying new types of aggregates to parameterize their characteristics. In the study carried out [18], it was noted that the compressive strength of concrete with the substitution of natural aggregate for recycled aggregate from ceramic waste varies in the order of -8% to -33.4% for substitutions of 25% to 100%, respectively, in relation to the strength of a control concrete.

Tests were carried out on the modulus of elasticity of the concrete when RCA was used, comparing the results in two ways, with the aggregate being saturated and dry. According to the results of tests carried out with natural aggregate, the modulus of elasticity of concrete increases in line with the concrete's compressive strength [19]. Concrete using 100% recycled aggregate has lower compressive strengths than conventional concrete with the same water/cement ratio [20].

In his study [21], as well as [10], he observed the behavior of concrete with recycled aggregate following Abrams' Laws, where he states that recycled aggregates have a greater influence on concrete strengths for lower water/cement ratios, assuming the behavior of Abrams' Law, the cement paste has greater resistance than the recycled aggregate.

Concrete with recycled aggregate has lower compressive strengths than conventional concrete, except for concrete with a water/cement ratio of 0.67, which is equal to reference concrete [22]. The greater porosity of recycled aggregates was detrimental to the concrete because they are less resistant than natural aggregates.

Concrete with recycled aggregate can achieve higher strengths than conventional aggregates [14]. This behavior can be attributed to the high absorption rate of aggregates, when not compressed in the production of concrete. This phenomenon alters the water/cement ratio and therefore increases mechanical strength [9]. Therefore, to use Recycled Concrete Aggregate, it is necessary to carry out a dosage study in a similar way to that already done for conventional concrete, establishing cement consumption, water, aggregates and their workability.

As the largest construction input, concrete has great potential to absorb a high demand for solid waste generated, if it is compatible with it, taking it out of circulation and incorporating it into its base structure, making sure that the aggregate meets the necessary quality and safety standards [23].

The use of construction waste can be an excellent alternative for solving problems with the reverse logistics of waste generated by the construction industry itself. However, due to the lack of studies and the absence of robust regulations, tons of resources are no longer used on construction sites every day. In view of the above, it is necessary to propose alternatives to add more information and apply it appropriately to the production of concrete with RCA, [9; 24].

The main objectives of this research were to contribute to the body of knowledge needed to make this possible, improving the understanding of the characteristics of concrete produced with recycled aggregates, reducing construction costs, increasing the safety of using recycled aggregates and evaluating the possibility of ARC replacing natural aggregate, by assessing mechanical strength.

II. METHODOLOGY

To determine the performance of concrete with recycled aggregate from concrete rejects (RCA), it was compared to a control concrete mix, 0% replacement mix, as shown in Table 1:

Table 1: Control mix and mixes with replacement of natural aggregate with RCA.

Mixes	C	AF	AM	B#0	b#1	RCA	water	additive
0%	334.00	335.00	459.00	180.00	980.00	0.00	175.00	3.34
25%	334.00	354.93	458.96	173.12	697.02	290.00	175.00	3.34
60%	334.00	354.93	458.96	94.16	396.93	696.00	175.00	3.34
100%	334.00	354.93	458.96	0.00	0.00	1160.00	175.00	3.34

Where: C: Cement; AF: Fine sand; AM: Medium sand; B#0: Gravel 12 mm; B#1: Gravel 25 mm; RCA: Recycled Concrete Aggregate;Additive.

The study determined the influence of various levels of replacement of natural aggregate with recycled concrete aggregate on the parameters of axial compressive strength and diametrical flexural tensile strength.

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The fixed parameters of the mix are cement and fine aggregates, which do not change according to the variation in the coarse fraction, which was replaced by 25%, 60% and 100% of the mass of the natural coarse aggregate by Recycled Concrete Aggregate. The additive content added to the concrete was varied according to the need for the concrete to reach the consistency of the reference concrete.

A. Materials and methods

All the raw materials used to make the concrete were supplied by a precast industry located in the region of Holambra, in the state of São Paulo, Brazil, and the same material was used to produce their concrete and, consequently, the waste under study. The crushed concrete as aggregate was acquired from leftover concrete and stored in a specific place for the trivial curing process. After its curing period, while still in its raw state, it was crushed using an adjustable jaw crusher with a mesh size of #20 mm and a maximum adjustment capacity of #40 mm. The materials that make up the concrete are listed below:

- ARI CP-V Portland cement.
- Coarse Aggregate (Basalt gravel #0, with specific mass 2.93 g/cm³, fineness modulus 5.58 and maximum aggregate diameter 9.5 mm and Basalt gravel #1 with specific mass 2.95 g/cm³, fineness modulus 6.77 and maximum aggregate diameter 19.0 mm).
- Fine aggregate (medium sand, with a fineness modulus of 2.41, specific mass of 2.60 g/cm³ and maximum aggregate diameter of 4.75 mm and fine sand, with a fineness modulus of 1.48 and specific mass of 2.64 g/cm³ and maximum aggregate diameter of 1.18 mm).
- Recycled concrete aggregate (run-of-mine, without sieving, with a specific mass of 2.32 g/cm³, fineness modulus of 7.14 and maximum aggregate diameter of 25.0 mm).
- Type II water-reducing additive based on polycarboxylates.
- Water from the public supply network.

B. Material characterization and concrete preparation

The physical tests of the coarse and fine aggregates were carried out in accordance with the specifications of the Brazilian Association of Technical Standards, through the Brazilian Regulated Standards (NBR):

- NBR NM 248 [25] - Granulometric composition of aggregates.
- NBR NM 46 [26] - Aggregates - Determination of the fine material that passes through the 75 µm sieve, by washing.
- NBR NM 53 [27] - Apparent specific mass and absorption of coarse aggregate.
- NBR 9775 [28] - Determination of surface moisture in fine aggregate - Chapman flask method.

The concrete was prepared at the precast company that supplied the waste, and the replacements were made in the coarse fraction of the mix. The concrete was prepared according to the method proposed by Helene and Terzian [29] for producing concrete in a concrete mixer, remaining in a damp chamber for 7 and 28 days until the mechanical test. Tests were carried out in accordance with ABNT specifications:

- NBR NM 67 [30] - Concrete - Determination of consistency by cone trunk slump.
- NBR 5738 [31] - Concrete - Procedure for molding and curing specimens.
- NBR 5739 [32] - Concrete - Compression test of cylindrical specimens.
- NBR 12142 [33] - Concrete - Determination of flexural tensile strength of prismatic specimens.

Recycled Concrete Aggregate was obtained from concrete rejects or waste produced by the precast company that generates the waste (Fig. 1). The waste comes from plastic concrete cured in the open air with different strength characteristics.

Figure 1: Precast concrete waste.

After being crushed using an adjustable jaw crusher with a minimum opening of 20 mm and a maximum of 40 mm, the final state was obtained (Fig. 2):

Figure 2: Recycled Concrete Aggregate (RCA).

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III. RESULTS AND DISCUSSIONS

The results obtained from the analysis of Recycled Concrete Aggregate when compared to aggregates of natural origin and when substituting natural aggregate in the manufacture of concrete are presented below.

A. Cement

The cement used for the tests was ARI CP-V Portland cement manufactured in the state of São Paulo, Brazil. The precast industry needs concretes that achieve high initial strengths for the casting of the parts produced, and such strength can be acquired more easily with High Initial Strength Portland cement (ARI).

The chemical and physical properties of the cement were supplied by the manufacturer according to Tables 2 and 3 and are in accordance with the specifications of the standard [34]:

Table 2: Chemical parameters of cement.

PF	MgO	SO3 p. C3A ≥ 8	RI	CO_2
4,48 %	5,66 %	3,65 %	0,49 %	1,36 %

Table 3: Physical parameters of cement.

# 200 (%)	# 400 (%)	Blaine (cm²/g)	Cement setting time (min)	End of setting of cement (min)	$fc_{,28}$ (MPa)
0,00	0,58	5312,00	159,00	210,00	51,80

B. Aggregate

- Dry specific mass and powdery material

When compared to natural aggregates (Fig. 3), RCA has a 21.43% lower specific mass. This behavior is consistent with the literature and can be attributed to adhered mortar, which is more porous and has a greater volume of voids, according to [12], [13] and [14].

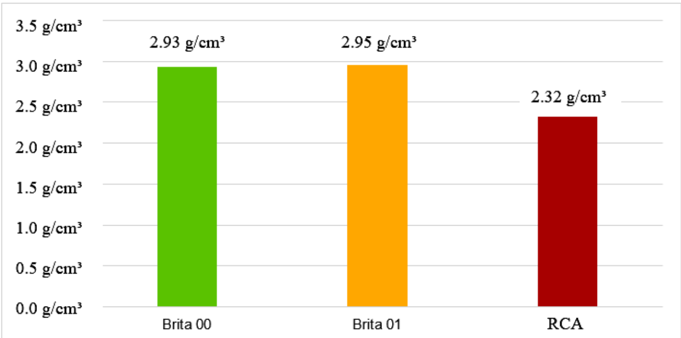

Figure 3. Specific mass of coarse aggregates, crushed stone and RCA.

This behavior of the material is close to what was analyzed by [10] and [15], where the specific mass of the recycled aggregate is up to 30% lower than the reference aggregate, making it plausible that it is in the mass range of the original concrete.

Contrary to expectations, the study material showed low levels of powdery material. This characteristic can be attributed to the processing method and the use of the fractions obtained during crushing [11], [15], (Fig. 4).

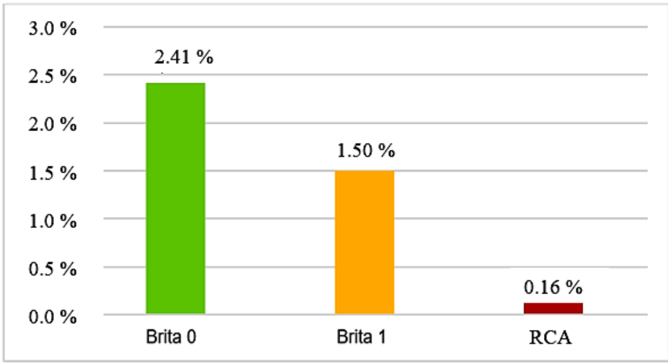

Figure 4. Content of powdery material.

- Specific mass of dry saturated surface

The RCA results for dry saturated surface specific mass are 17.59% lower than the natural aggregates, a result that was already expected and is consistent with the dry specific mass values. These results confirm the lower density of the material compared to the natural aggregate (Fig. 5).

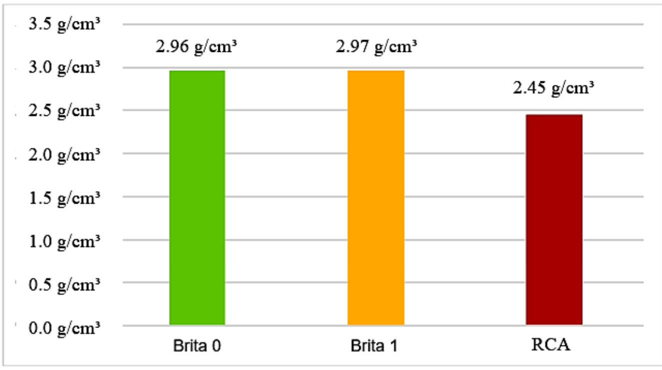

Figure 5. Specific mass of dry saturated surface.

It can be seen that RCA, when compared to natural aggregates, has a specific mass 21.43% lower. This behavior is in line with the literature and can be attributed to adhered mortar, which is more porous and has a greater volume of voids [12], [16], [10]. This behavior of the material is close to what was analyzed by [10] and [11], where the specific mass of the recycled aggregate is up to 30% lower than the reference aggregate, a plausible value for the mass of the recycled aggregate to be like that of the aggregate that originated it.

- Absorption

Because of its more porous characteristics, due to the adhered mortar, RCA has an absorption rate approximately 5 times higher than natural aggregate. These values are close to those of [9], where coarse RCA had an absorption rate of 4.95%, and not far from those of [16], with 6.69% (Fig. 6).

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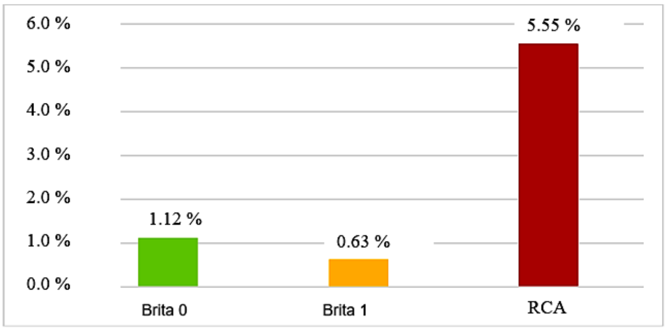

Figure 6. Absorption of coarse aggregate and RCA.

- Aggregate granulometry

The fineness modulus of the aggregates indicates the size of their particles, i.e. the higher the fineness modulus, the finer the aggregate; higher fineness moduli indicate a greater need for paste to lubricate the aggregates. The difference in fineness modulus between the aggregates is gradual, since the comparison is of aggregates from different granulometric ranges, recycled coarse aggregate has a higher fineness modulus than natural gravel 01 [14].

The higher fineness modulus classifies recycled coarse aggregate in a higher particle size range, but recycled coarse aggregate does not fit into any particle size range prescribed by the standard [34], falling between gravel 01 and gravel 02, results consistent with [8], [9] and [14].

The particle size curve of the Recycled Concrete Aggregate is continuous, a relevant factor for concrete production, and despite having values outside the normative specifications (since no beneficiation by sieves was used), the recycled coarse aggregate (RCA) was used without any manipulation of its particle size, to use it with the least possible influence on its beneficiation (Fig. 7).

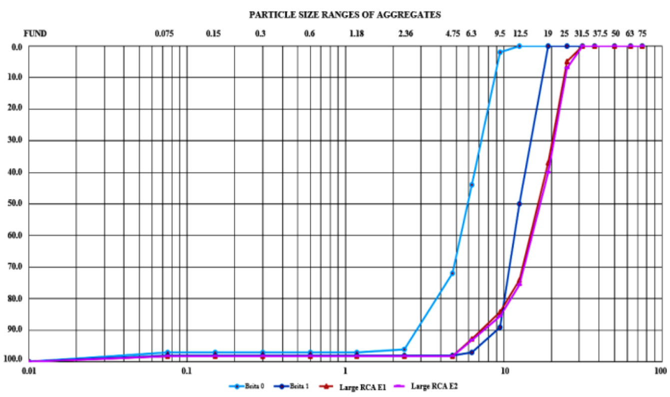

Figure 7. Particle size curve of coarse aggregates and RCA.

The results show that the material under study is susceptible to large variations in particle size. It is therefore important to define how the material will be processed and to characterize it before it is used.

C. Concrete

- Workability

Concrete with recycled aggregate has a lower workability than conventional concrete (Fig. 8), [9]. According to [10], [17], and [11], this difference can be attributed to the rougher texture of recycled aggregate, which causes the paste to lock, reducing workability when compared to natural aggregates. The greater absorption of ARC can also be attributed to a factor that reduces the workability of the concrete, since it absorbs part of the mixing water, reducing the water/cement ratio of the concrete and, in turn, its workability.

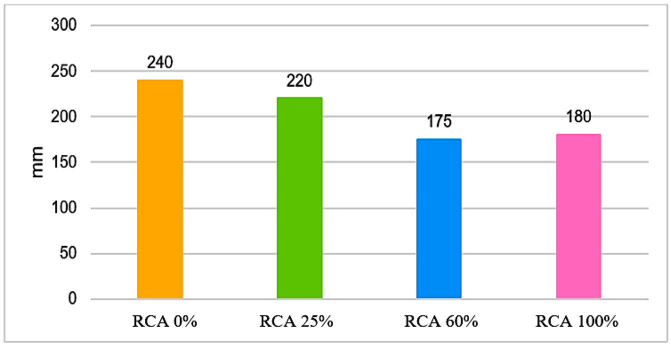

Figure 8. Workability of concretes with substitution in relation to the standard.

The control mix, RCA 0%, behaved as initially studied, 220±20 mm, reaching a slump of 240 mm without any addition or cutting of water or additives. The concrete had good workability and was light, opening easily.

The RCA 25% mix used all the water in its mix and required a further 20g of additive to bring it close to the workability of the control mix. Despite reaching a workability of 220 mm, the concrete was heavier and more cohesive. This characteristic can be attributed to the shape of the recycled aggregate, which locks the mortar in place.

The RCA 60% mix used all the water in its mix and needed another 40g of additive to bring it close to the workability of the control mix. However, due to its instability, it was not possible to reach the 220 mm slump. It was more difficult to handle. Even though its slump was 175 mm, there was no shear collapse during the slumping process.

The RCA 100% mix used all the water in its mix and required a more aggressive approach. Another 150g of water and another 50g of additive were added to bring it close to the workability of the control mix. However, due to its greater demand for water and/or superplasticizers, the dosages were not increased to obtain a 220 mm slump. It showed greater cohesion even though its consistency reached the 180 mm slump.

- Compressive strength

The concrete produced with recycled aggregate, with substitutions of 25% and 60%, achieved higher compressive strengths than the reference mix (Fig. 9). The mix with 100% recycled aggregate has a negligible reduction compared to the reference.

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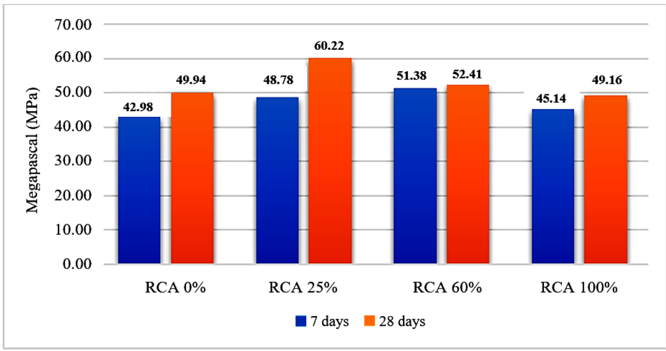

Figure 9. Compressive strength of control and replacement concrete for 7 and 28 days.

The behavior presented by the concrete is in line with the results presented by [22], who obtained concretes with recycled aggregate with higher compressive strengths than the reference concretes, but there was a decrease in the modulus of elasticity. On the other hand, [15], [17] and [18] observed that concrete with recycled aggregate can have higher compressive strengths than conventional aggregates, where this behavior can be attributed to the high rate of absorption of the aggregate not compensated for in its pre-production [22] and [20]. This phenomenon alters the water/cement ratio, decreasing it and, according to the behavior of Abrams' Laws, the concrete tends to have higher strengths.
For this behavior to be effective, [21] states that the recycled aggregate must have a higher strength than the cement paste, because in his studies of richer mixtures, i.e. where the cement paste had a high strength, the recycled aggregate failed.

- Flexural tensile strength

The flexural tensile strength of concrete decreases as the recycled concrete aggregate content increases (Fig. 10) [15]. This behavior is in line with that presented by [9], who points out that the flexural tensile strength of concrete drops considerably with any percentage of recycled aggregate added.

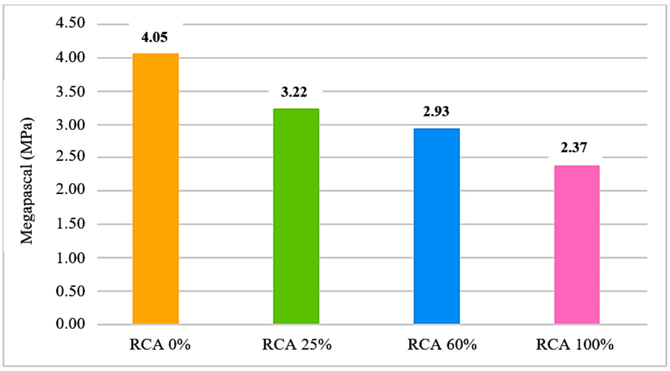

Figure 10. Flexural tensile strength of control and replacement concrete at 28 days.

This drop in performance can be attributed to the greater fragility of this property with a larger paste-aggregate transition zone, so the paste/aggregate itself is an element with low tensile strength.

IV. CONCLUSIONS

Reducing production costs and concern for the environment can be factors in leveraging the use of recycled materials by creating new means or methods of production, whether on a large or small scale. The growing generation of construction waste is the starting point for expanding the body of research into materials that can be incorporated back into concrete, making the reverse logistics of construction waste more effective by reinserting waste material into the production chain.
Despite all the bibliographic references, it is necessary to broaden the range of research into recycled concrete aggregates. There is no established methodology or standard to support this type of research, making the results scattered in comparison with other authors.
With the aim of expanding the body of research into recycled concrete aggregates, this study evaluated the behavior of different proportions of recycled concrete aggregate in terms of compressive strength, flexural tensile strength and diame-tral tensile strength, as well as evaluating some of the physical properties of recycled concrete aggregates.
Despite the positive results of this study regarding the use of this material in the composition of new concretes, the process still needs to be improved, since both the source material and the method of processing it need to be studied. There is no specific standard to help with these definitions, so before this product can be used on a large scale in Brazil, it is necessary to reduce the uncertainties in the processing and dosing methods, to guarantee the safety of using this product and make it viable for use.

The following conclusions can be drawn from the experimental program presented:

- Recycled Concrete Aggregate has a dry specific mass up to 21.43% lower than natural reference aggregates, as well as having a dry saturated surface specific mass up to 17.59% lower than natural reference aggregates. These reductions mean that there is a need to compensate for the volume of recycled concrete aggregates when used in conventional concrete.
- The absorption rate of recycled concrete aggregates is 5.55%, which is quite high. It is therefore necessary to take this parameter into account when composing the mix, in order to avoid loss of concrete workability due to absorption of the concrete mixing water, as reinforced by the standard [8; 9] on pre-wetting the aggregates.
- The content of powdery material found in the research is not in line with the bibliographic reference. This characteristic can be attributed to the method of processing the material for use in the research.
- The particle size curve of the Recycled Concrete Aggregate shows that the RCA sample evaluated had a discontinuous particle size, which is important to produce concrete as it causes a better arrangement between the particles.
- The particle size curve of the Recycled Concrete Aggregate does not fit within the particle size curves specified by the standard [35], falling between gravel 1 and 2. Thus, there is a need to adjust and balance the mix in terms of the particle size curve of the concrete and its workability. However, it

is important to note that direct substitution brought excellent mechanical results, so the effect should be weighed up.

- The fineness modulus of recycled concrete aggregate is greater than that of natural aggregate. It therefore has larger particles.
- Concrete with recycled aggregate was less workable than reference concrete. This characteristic can be attributed to the greater absorption and roughness of the Recycled Concrete Aggregate, which reduces the amount of water available for the paste.
- Even though the workability of concrete with recycled aggregate is improved by using plasticizer or water (in the case of the mix with 100% recycled aggregate), as trivially stated in technical references and normative guidelines, the slump test results do not match the real workability of the concrete. They were more difficult to handle, which can be attributed to the rougher texture of the recycled aggregate, as it causes the paste to lock, reducing workability when compared to natural aggregates.
- Concrete with Recycled Concrete Aggregate needs a moisture content in the mix to produce the same consistency/workability as conventional concrete. This parameter is not recommended due to the reduction in the water/cement ratio, and it is better to improve workability with the use of plasticizing or super-plasticizing additives. It should be noted that the absorption parameter of the Recycled Concrete Aggregate was not considered when adjusting the mix.
- The concrete mixes that used recycled aggregate with substitutions of 25% and 60% achieved higher compressive strengths than the RCA 0% reference mix, while the mix with 100% recycled aggregate, despite not having a higher compressive strength, had a reduction close to that of the control. This behavior can be attributed to the reduction in the water/cement ratio, obtained by absorbing the mixing water from the Recycled Concrete Aggregate, which increases the strength of the cement paste. For this parameter to be effective, the recycled aggregate must have a higher strength than the cement paste.
- The flexural tensile strength tends to be lower in all concretes with some addition of recycled concrete aggregate. The flexural tensile strength for concretes with up to 60% substitution fell by up to 4.70% compared to the reference concrete, but with the total use of recycled aggregate the drop was more significant, at 18.92%. This behavior can be attributed to the greater fragility of Recycled Concrete Aggregate, as it is less porous and the Transition Zone between the paste and the aggregate becomes a fragile point.
- It can be concluded that the use of Recycled Concrete Aggregates is perfectly possible without the 20% restriction in the standard [8] in terms of mechanical performance, given due consideration of their shortcomings, such as lower workability and lower tensile strength and determination of their durability.
- The lower flexural tensile strength of concrete with the addition of Recycled Concrete Aggregate needs to be considered when calculating structural elements, as it will cause greater deformations.
- Although the results evaluated show positive data, it is necessary to evaluate the other concrete properties not evaluated in this study, as well as increasing the volume of tests to assess the constancy and variability of the application results.
- Finally, based on the results obtained in this research, it is possible to state that there is a great possibility of applying recycled concrete aggregates in new concrete compositions. However, there is a need to create specific evaluation methods, so that repeatability brings a greater volume of data and data comparison.

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