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Evaluation of the Characteristics of Recycled Aggregates Produced in Campinas-SP/Brazil

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ABSTRACT

To use the aggregate generated by recycling plants in the production of concrete, it is essential to know its characteristics. This paper aims to evaluate samples of recycled aggregates, both small and large, produced at two recycling plants located in the city of Campinas, SP, Brazil, comparing the results with parameters established by NBR 15116:2004 and with the characteristics of the natural aggregates used in the production of concrete. For the development of the study, samples of aggregates, small and large, both natural and recycled were collected, which had their characteristics determined and evaluated according to the specifications of NBRs 7211:2009 and 15116:2004. The results indicate that even the recycled aggregates showing some variability throughout the tests and unfulfilled with some normative specifications, it is concluded that their use in concrete is close to becoming feasible. It was verified that simple corrections in the recycling plants or additions of a certain amount of natural aggregate, would probably already be enough for the total standardization of the recycled aggregate. Comparing the recycled aggregates with the natural ones it was verified that the recycled ones present a higher index of fines and mainly greater absorption of water, which reflects in smaller values of specific mass, apparent specific mass and crushing resistance. However, these are not limiting factors in the use of recycled materials in concretes without structural function, since they will not be so mechanically required.

1. INTRODUCTION

Civil construction is a major consumer of natural resources, and is a major generator of construction and demolition waste (CDW). Such wastes are generally non-toxic, but present problems related to their final disposal, and they occupy huge areas that could be used for other purposes [1].

Most CDW generated in the cities, about 75%, come from small construction, construction, renovation and demolition, carried out informally by the property users, thus there are irregular dispositions on sidewalks, vacant lots, public dumps, squares, among other places [2].

According to the Solid Waste Survey in Brazil [3], the Brazilian cities collected about 45 million tons of CDWs in 2017. It is emphasized that the amount of waste generated is possibly much greater than that presented, since the cities, as a rule, collect only the waste discharged or abandoned in the public places.

In Brazil, in 2017, approximately 124 thousand tons of CDW were collected per day, which represents an index of 0.600 kg / inhabitant / day [3]. The generation of construction waste in new buildings is 300 kg/m^2 in Brazil, while in some more developed countries it reaches on 100 kg/m^2. The answer to this delay may lie in the fact that Law No. 12.305 [4], which establishes the National Solid Waste Policy (PNRS), was implemented only in 2010, after many years of discussions in the National Congress involving the three federated entities – Union, States and Cities, the productive sector and civil society [1].

In the PNRS, there is a specific chapter on CDW that says about the difficulties of managing them, where they find obstacles in the ignorance of the nature of the residues and the absence of culture of separation, among other reasons, thus the studies on the subject are essential. Summarizing, the chapter of the PNRS that deals with CDW aims at stipulating goals for management, making it clear that responsibility is handled by the generator, following the guidelines, criteria and procedures proposed in the CONAMA Resolution No. 307/2002 [5].

In the European Union, there is no specific legislation for CDW as exists for the other types of waste, but some countries have taken the initiative to create public policies to reduce waste, with reference to Denmark, which achieves a rate of 81% recycling in the CDW, waste recycling in that country has become a current practice. And to achieve this efficiency, the government uses two practices, waste that is not recycled is subject to high tax rates and the separation of waste at its origin is mandatory [6].

The generation of recycled aggregate is done through mobile or fixed recyclers, both of which have the function of transforming the aggregates from CDW into recycled raw material such as sand, gravel hail, among others. The process inside the plant is summarized in three stages; in the first, the material received in the recyclers is submitted to a visual inspection in the buckets, with the aim of rejecting materials with many contaminants or with a high heterogeneity [7].

If the material is able to enter the plant, it is discharged in a primary pile; then the material passes through a sieving in order to remove present soils. After the first sieving, the material is transferred to a conveyor belt where the contamination (plastics, glass, cans, organic matter, etc.) are manually collected. With the "cleaned" material the crushing step is carried out, which reduces the size of the particles; finally, the material is sieved and stored in piles according to the granulometry of the aggregate.

The mineral fraction that is crushed to produce recycled aggregate, conforms to CONAMA No. 307/2002 [5] as class A, are materials such as bricks, blocks, tiles, concrete, soils, rocks, and pavements waste. However, as mentioned above, even the soils conforming to class A waste, almost unanimously they are removed from the crushing process.

In order to establish the usage requirements of the recycled aggregates, NBR 15116:2004 [8] was developed, which establishes the properties of the recycled aggregates to be used for concrete production, such as water absorption capacity, fines content, clay clods, among others. This standard also establishes the maximum limits for such properties, in order to destine the recycled aggregate for concrete production without structural function and pavement.

The main problem with the production of recycled aggregates is the heterogeneity of their raw material that is CDW are composed of several dimensions and material fractions, the largest volume being inert materials, ranging from 40% to 85% of the total produced in a construction. With this information, it is possible to notice the enormous variety of the residues produced in the construction and demolition, which can be propagated to the final product, the aggregate [9].

Even though there is good sorting in the recycling plants, for the use of the recycled aggregate in the Jobs defined in NBR 15116:2004 [8], it is essential to study and to know the physical and chemical characteristics of the recycled aggregates, since they can vary due to their source.

This study aimed to evaluate the composition and variability of the aggregate characteristics of the recycled waste from the recyclable units of the region of Campinas, Brazil, through physical and chemical tests established in NBR 15116:2004 [8]. The natural aggregates were also evaluated according to the same parameters for later comparison with the recycled aggregates.

2. MATERIALS AND METHODS

The research methodology adopted was experimental method, considering trials that aim at the characterization of aggregates from class A waste treated for application in concrete production.

Samples of both small and large recycled aggregates were collected from two class A waste recycling plants in Campinas-SP/Brazil, one located in Barão Geraldo district and the other located adjacent to the Delta Sanitary Landfill complex, also collected natural aggregates in storage of building materials in the city of Itapira-SP/Brazil, specifically port sand and gravel 1 of diabase. For the aggregates of the Barão Geraldo plant, two collections were made, while for the aggregates collected in the Delta and in the deposit of construction materials a collection was carried out.

In order to facilitate the identification of the aggregates during the study, creating a standardization, they were shortened by their origin, followed by the size, location and number of collections as shown in Table 1.

Table 1. Aggregates abbreviation

Origin	Size	Location	Collection	
Natural or Recycled	**Small or Large**	**City of Plant**	**Collection number**	**Abbreviation***
Natural	Small	Itapira	1	ANMI
Natural	Large	Itapira	1	ANGI
Recycled	Small	Barão G.	1	ARMB1
Recycled	Large	Barão G.	1	ARGB1
Recycled	Small	Barão G.	2	ARMB2
Recycled	Large	Barão G.	2	ARGB2
Recycled	Small	Delta	1	ARMD
Recycled	Large	Delta	1	ARGD

*) In case of only collection, no numbering was use in the abbreviation.

The granulometric composition (granulometric curve, maximum diameter and modulus of fineness), water absorption, total salts, chlorides, sulfates, non-mineral materials, clay clods, material content in the mesh 75µm (fines), specific mass and apparent specific mass. While for the large material in addition to the same determinations the determinations of the following properties were included: content of cement and rock fragments, and crushing resistance. The characteristics of the aggregates were obtained according to the technical norms presented in Table 2.

It should be noted that for each sample tested for the above properties, three repetitions of determinations were performed, the result being the arithmetic mean of the results obtained in each repetition, along with the mean the standard deviation was presented. Except for the total salt, chloride and sulfate tests, which were performed with two repetitions, the result being the highest value obtained, such treatment of the data in the salt assay allowed a higher margin of safety regarding the normative requirements. The property of crushing resistance was performed only with a determination, because it required a high amount of sample.

Table 2. Assayed properties and technical norms

Properties	Small aggregate	Large aggregate
Granulometric composition [10]	NBR NM 248	NBR NM 248
Water absorption [11, 12]	NBR NM 30	NBR NM 53
Salts, Clorides and Solubles sulfate [13]	NBR 9917	NBR 9917
Clay clods [14]	NBR 7218	NBR 7218
Fines – Material contente in the mesh 75 µm [15]	NBR NM 46	NBR NM 46
Content of cement and rocks based fragments [8]	-	NBR 15116 – Attachment A
Non-mineral materials [8]	NBR 15116 – Attachment B	NBR 15116 – Attachment A
Specific mass and Apparent specific mass [12-16]	NBR NM 52	NBR NM 53
Crushing Resistance [17]	-	NBR 9938

The tests developed are those referring to the characterization properties imposed by NBR 15116:2004 [8] and by NBR 7211:2009 [18] which present the requirements for the recycled aggregates for the preparation of concrete without structural function and for the natural aggregates destined to the preparation of concrete.

3. RESULTS AND DISCUSSION

3.1 Granulometric composition

Samples of small and large aggregates were collected and prepared according to NBR NM 26:2009 [19] (Aggregates – sampling) and NBR NM 27:2001 [20] (Aggregates – Reduction of the field sample for laboratory tests).

The determination of the granulometric composition was determined following the requirements of NBR NM 248:2001 [10], using sieves with metallic screens that comply with NBR NM ISO 3310-1:1997 [21].

The results obtained are related to the grain size curve, shown in Figure 1 for the small aggregates and in Figure 2 for the large aggregates. The fineness module values are shown in Table 3, and finally the maximum diameter values in Table 4.

The standard NBR 15116:2004 [8], which imposes requirements on recycled aggregates for use in structural endless concrete, establishes that the granulometric composition of the aggregates must be in accordance with NBR 7211:2009 [18]. Which requires the small aggregates for the preparation of concrete are with their grain size curve preferably contained in the optimal granulometric zone or at least in the upper or lower usable zones.

The ANMI has 50% in the lower usable zone and 50% in the optimal zone. The ARMB1 and ARMD have their highest percentage in the upper usable zone, with 40% and 30% respectively in the optimal zone. The ARMB2 follows the same.

The granulometric curves for the child aggregates, ANMI, ARMB1 and ARMD meet normative requirements effectively. Although the ARMB2 does not meet the standard, it can have its grain size curve corrected with the addition of a certain amount of normalized natural sand, which would shift its curve to the right, so possibly it would be inside some allowed zone; NBR 15116:2004 [8] allows this feature.

To the recycled aggregates with NBR 15116:2004 [8], it also imposes that they meet the granulometric composition of NBR 7211:2009 [18], which requires that the large aggregates are included within some granulometric zone, which starts in gravel 0 (4.75/ 12.5 mm) and goes to 4 (37.5 / 75 mm) gravel. Figure 2 shows the granulometric zones of gravel 1 (9.5 / 25 mm) and gravel 2 (19 / 31.5 mm), due to the fact that the analyzed aggregates are apparently contained between one of the two zones.

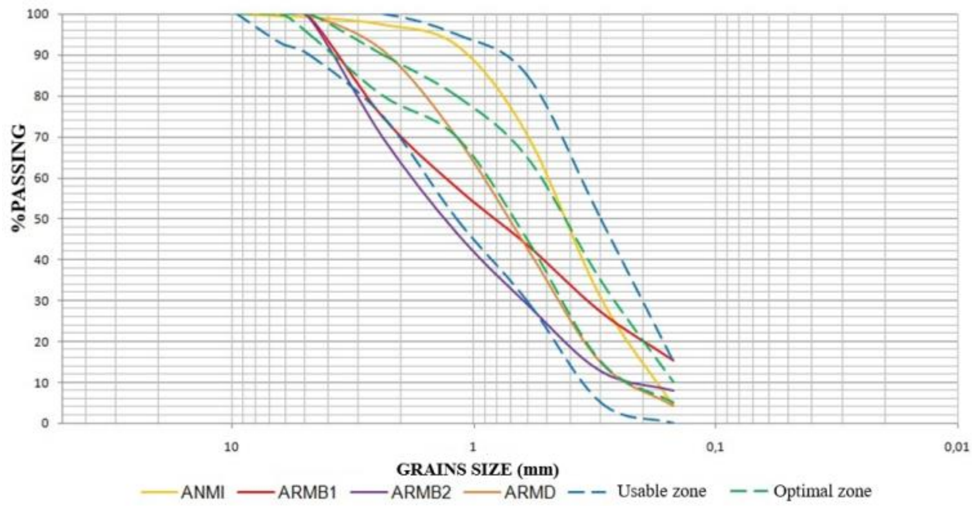

Figure 1. Granulometric curve of small aggregates

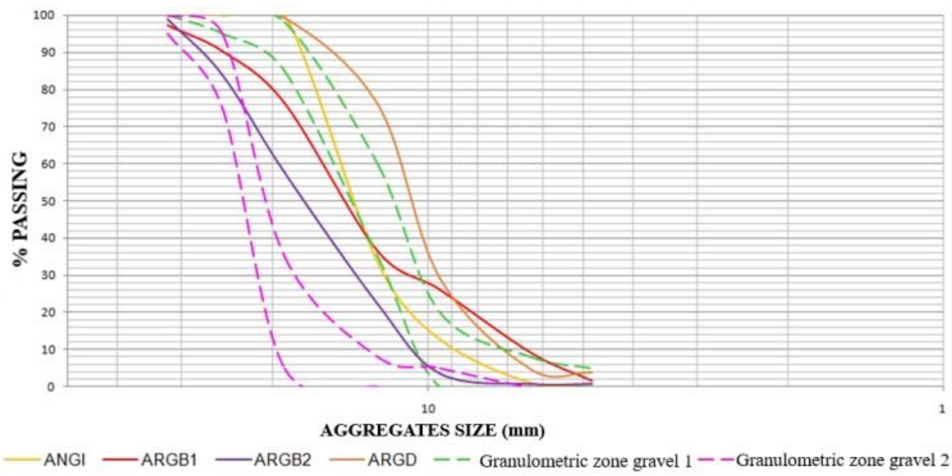

Figure 2. Granulometric curve of large aggregates

Table 3. Module of fineness of the aggregates small and large

Small Aggregate	**Module of Fineness** (arithmetic mean ± standard deviation)	Requirements 7211:2009 - Zones		
		Optimal	**Usable lower**	**Usable upper**
ANMI	2.06 ± 0.12	2.20 to 2.90	1.55 to 2.20	2.90 to 3.50
ARMB1	2.82 ± 0.07			
ARMB2	3.35 ± 0.14			
ARMD	2.77 ± 0.03			
Large Aggregate	**Module of Fineness** (arithmetic mean ± standard deviation)	**Requirements 7211:2009**		
ANGI	5.84 ± 0.03	Not included		
ARGB1	5.90 ± 0.25			
ARGB2	6.35 ± 0.09			
ARGD	5.53 ± 0.03			

Table 4. Maximum diameter of small and large aggregates

Small Aggregate	**Maximum diameter (mm)** (arithmetic mean ± standard deviation)
ANMI	2.36 ± 0.00
ARMB1	4.75 ± 0.00
ARMB2	4.75 ± 0.00
ARMD	4.75 ± 0.00
Large Aggregate	
ANGI	19 ± 0.00
ARGB1	32 ± 0.00
ARGB2	32 ± 0.00
ARGD	19 ± 0.00

Only ANGI complied with the requirement, it was understood within the granulometric zone of gravel 1, because it is a natural aggregate which is more required in mechanical terms, there is higher normative attention in its confection inside the quarries.

ARGB1 and ARBG2 presented percentages of material in gravel zones 1 and 2, with the highest percentage in a zone not established by the standard, therefore the two materials are not fit to use.

The ARGD is also not fit to use, however it is noted that its grain size curve is close to the gravel zone 1, so if there is an addition to be stipulated of large aggregate as dimensions slightly larger than the ARGD, the curve possibly takes off to the left in the gravel zone 1.

The fineness module of the ARMB1 and ARMD is in the optimal zone, even adding or subtracting the value of the standard deviation in the arithmetic mean they persist in the optimal zone. The ANMI an ARB2 were included in the usable zones, the lower ANMI and the upper ARMD. All small aggregates tested met the requirement of the standard, it is emphasized that ARMB1 and ARMD obtained better results than the natural aggregate (ANMI).

The NBR 7211:2009 [18] does not stipulate limits of fineness module to the large aggregates; by the framing in the zones of different dimensions of gravel, the evaluation of the granulometric composition is done. The results obtained served to analyze the variability of the dimensions of the aggregates, the ANGI, ARGB2 and ARGD demonstrate low values of standard deviation, and this means that the variation between the three determinations was small.

ARGB1 presented higher variation, but the major problem regarding ARGB1 was its change from ARB2. As the two aggregates come from the same plant, ideally, their values would be close, since the production process is the same; the disparity in values reflects problems of quality control of the aggregate inside the plant.

The maximum diameter (Table 4) or maximum dimension characteristic is a quantity associated with the granulometric distribution of the aggregate, corresponds to the nominal opening, in millimeters, of the sieve mesh of the normal or intermediate series in which the aggregate presents an accumulated retained percentage equal to 5 % or less than 5% of the mass.

All of the recycled small aggregates had the same value of 4.75 mm, which is characterized by having a thicker sieve band than the ANMI (2.36 mm).

The ARGB1 and ARGB2 have a maximum diameter of 32 mm, which is related to the granulometric distribution of the same, which brings a percentage of the samples to granulometric gravel zone 2. Thus, the ARGB1 and ARGB2 are in the gravel zones 1, 2 and another non-standard strip, so the samples do not fit in any zone. A possible solution of the problem would be to reduce the opening of the first crusher of the plant to reduce the maximum diameter; this alteration would interfere in the granulometric distribution, leaving the aggregate closer or even within the gravel zone 1.

3.2 Content of fragments based on cement and rocks and non-mineral materials

The large aggregates were tested for the content of cement – rock fragments and non-mineral materials by a visual analysis method contained in Attachment A of NBR 15116:2004 [8]. They are classified as mixed recycled aggregate (AMR), which presents less than 90% of cement-rock fragments or recycled concrete aggregate (ARC), which contains more than 90% of rocky and cementitious material.

For the small aggregates, there is no standard specifying the determination of the content of cement-rock fragments, but for the determination of non-mineral materials, Attachment B of 15116:2004 [8] regulates the test.

Therefore, Table 5 presents the classification of the large aggregates as to their composition, and the percentage of non-mineral materials for both aggregates.

All recycled aggregates were classified as ARC – aggregate of concrete residue, composed of at least 90% by mass of Portland cement-based fragments and rocks [8]. The ANGI, for being completely natural, corresponded to the expectations of composition and not contamination by non-mineral materials.

In the case of non-mineral materials, all large recycled aggregates met the standard. It was observed that the standard deviations obtained were high in relation to the means, with ARGB2 reaching the mean value and ARGB1 being higher than the mean, because the value for non-mineral materials was zero, causing major variations.

Table 5. Content of cement and rocks-based fragments and non-mineral materials of large aggregates

Small Aggregate	Cement and Rocks Fragments (%) (arithmetic mean ± standard deviation)	Requirements 15116:2004		Non-Minerals (%) (arithmetic mean ± standard deviation)	Requirements 15116:2004
		ARC	ARM		
ANMI	-	-	-	1.57 ± 0.65	≤2
ARMB1	-	-	-	0.44 ± 0.14	
ARMB2	-	-	-	1.98 ± 0.48	
ARMD	-	-	-	10.34 ± 0.88	
Large Aggregate					
ANGI	100.00 ± 0.00	≥90	<90	0.00 ± 0.00	≤2
ARGB1	98.27 ± 1.46			0.13 ± 0.23	
ARGB2	90.93 ± 0.87			0.18 ± 0.18	
ARGD	97.77 ± 1.10			0.30 ± 0.22	

An important information that can be observed by analyzing Table 5 is that by subtracting the value of non-mineral materials and the content of fragments based on 100% cements and rocks, we have the value of the ceramic fragments of the large samples. Thus, the average percentage of ceramic fragments in the sample is 1.6% for ARGB1, 8.89% for ARGB2 and, finally, 1.93% for ARGD.

The ANMI presented with a relative amount of non-mineral materials, which are derived mainly from the branches that composed the samples. ARMB1 met the normative requirements, while ARMB2, an aggregate from the same plant, had the average value inside the allowed; however, when adding the value of the standard deviation it extrapolates the norm, these values demonstrate a certain variability within the productive process of the plant. The ARMD did not comply with the required, its average value was more than five times greater than allowed, and this high mount of non-mineral materials is resulting from bitumen contained in the samples. As 15116:2004 [8] does not specify any test method for the content of cement and rocks-based fragments for small, there was no way to know exactly which classification fit into ARC or ARM. However, in visual analysis, ARMB1, ARMD and mainly ARMB2 presented a certain red coloration, which represents the addition of ceramic fragments to the aggregate, such as tiles and bricks, in order to compare them with the normative requirements, which the other properties of the aggregates were subject, classified them as ARM.

3.3 Water absorption capacity

The water absorption capacity was determined according to NBR NM 30:2001 [11] (Small. aggregate-Determination of water absorption) and NBR NM 53:2009 [12] (Large Aggregate-Determination of specific mass, apparent specific mass and water absorption); the results are shown in Table 6.

The small-recycled aggregates were classified in item 3.2 as ARM, so all were able to meet the requirements, even when compared to the maximum value for ARC, they met the standard.

The large recycled aggregates, even adding up the standard deviation value in the arithmetic mean, all still showed a result below the value of ≤7% at which the ARC complies with the limit specified by NBR 15116:2004 [18].

It is verified that although the recycled aggregates, both small and large, meet the norm, they have high absorption values compared to the natural ones, verified values that reached the order of 7.5 times greater.

Table 6. Water absorption of small and large aggregates

Small Aggregate	Water absorption (%) (arithmetic mean ± standard deviation)	Requirements 15116:2004	
		ARC	ARM
ANMI	2.89 ± 0.53	≤12	≤17
ARMB1	9.65 ± 0.87		
ARMB2	11.42 ± 0.86		
ARMD	11.26 ± 2.46		
Large Aggregate			
ANGI	0.85 ± 0.05	≤7	≤12
ARGB1	5.60 ± 0.79		
ARGB2	6.40 ± 0.32		
ARGD	5.86 ± 0.49		

3.4 Soluble salts, chlorides and sulfates

The soluble total salts, chlorides and sulphates contents were determined as specified by 9917:2009 [13]. The NBR 15116:2004 [8] establishes maximum values of soluble chlorides and sulfates present in the recycled aggregates, destined to the preparation of concretes without structural function. The salt contents were tested to complement the studies, but are not required by the standard. The results are shown in Table 7.

The standard NBR 9917:2009 [13] requires that the individual values must be within a range of ± 10% of the average value; this requirement was not reached, since the values obtained are extremely small, thus achieving an accuracy of 10% means to have a variation of approximately 0.00001% for chlorides, for example, something very difficult to achieve. Therefore, the results set forth in Table 7 refer to the higher result of the two determinations; such treatment ensures a safer analysis of the data. It is emphasized that the values of the two determinations remained in the same order of scalar magnitude.

The results obtained prove the viability of the small and large recycled aggregates tested for the absence of salts, chlorides and sulfates. Standard 15116:2004 [8] says that the percentage of chlorides and sulfates cannot exceed 1% per sample. All the results are below what the standard establishes as maximum; therefore, all comply with the norm 15116:2004 [8] for chlorides and sulfates in an extremely satisfactory way. In addition to the results that meet the standard 15116:2004 [8] that only specifies requirements for recycled aggregates, almost all also meet the maximum limits of chlorides and sulfates of NBR 7211:2005 [18]. These limits are:

- Chlorides content: <0,2% for single concrete; <0.1% for reinforced concrete and <0.01% for prestressed concrete;
- Sulfates content: <0.1% for both concrete.

Table 7. Content of salts, chlorides and soluble sulfates of small and large aggregates

Small Aggregate	**Total salts (St) (%)** (highest value)	**Chlorides (Cl^-) (%)** (highest value)	**Sulfates (SO_4^{2-}) (%)** (highest value)	**Requirements 15116:2004**		
				St	**Cl^-**	**SO_4^{2-}**
ANMI	0.27	0.000067	0.021			
ARMB1	1.56	0.000111	0.356			
ARMB2	0.28	0.000067	0.047			
ARMD	0.54	0.000332	0.119			
Large Aggregate					≤1	≤1
ANGI	0.23	0.000027	0.009			
ARGB1	0.37	0.000089	0.050	-		
ARGB2	1.18	0.000067	0.091			
ARGD	1.00	0.000106	0.061			

Only ARMB1 and ARMD do not meet the sulfate content requirements of NBR 7211:2005 [18], but meet the requirements of chlorides. The remaining samples meet the requirements of chlorides and sulfates, even for use in prestressed concrete. Comparing the values of the natural aggregates with the recycled ones is observed that the contents of the natural ones were smaller. Although the total salts contents are not required by norm, it is recommended their determination in the recycling plants in order to indirectly determine the chloride and sulfate contents, standardizing the aggregate for use.

Although the total salts contents are not required by norm, it is recommended their determination in the recycling plants in order to indirectly determine the chloride and sulfate contents, standardizing the aggregate for use. When the total salt content is obtained, the sum of chlorides, sulfates and other salts is obtained in this value, therefore, if the value obtained is less than 1%, as verified in most of the clusters shown in Table 7, the values of chlorides and sulfates must also be less than 1%, thus complying with the normative requirement.

The chloride and sulfate test requires reagents and high-cost equipment, such as silver nitrate, specific electrode, muffle oven, among others, and the methods are complex in execution, while the salt test is simple to perform and does not requires expensive reagents and equipment, just a few glassware and a simple magnetic stirrer.

3.5 Passing material content of the mesh 75 µm

The fines content of the analyzed aggregates was determined according to NBR NM 46:2003 [15] (Aggregates–Determination of the fine material passing through the75-µm sieve, per wash). The contents are set out in Table 8.

Analyzing the values for the small aggregates, as expected the ANMI had the lowest content of fines, and the ARMD was relatively close to the natural value. ARMB1 and ARMB2 presented close values, in this way is observed a small variability of one collection to the other, this shows that the plant maintained a production pattern as regards to the small aggregate.

The ANGI obtained the lowest result of the large, but the ARGB1 and ARB2 were very close to their value, the ARGD was that presented higher content of the fine aggregates, but nothing that would compromise it within the limits of the norm.

As for the conditions imposed by the standard all small and large have met the requirements, all are below the maximum values of fines.

Table 8. Fine content in small and large aggregates

Small Aggregate	**Fine Content (%)** (arithmetic mean ± standard deviation)	**Requirements 15116:2004**	
		ARC	**ARM**
ANMI	1.25 ± 0.58		
ARMB1	8.54 ± 0.69	≤15	≤20
ARMB2	8.25 ± 1.05		
ARMD	3.48 ± 0.57		
Large Aggregate			
ANGI	0.20 ± 0.18		
ARGB1	0.54 ± 0.32	≤10	≤10
ARGB2	0.96 ± 0.34		
ARGD	1.66 ± 0.11		

3.6 Clods of clay

It was determined the property of clay clods following methodological precepts exposed in NBR 7218:2010 [14] (Aggregates-Determination of clay content in clods and friable materials). The determinations obtained for the tested aggregates are shown in Table 9. Only the natural aggregate (ANMI) among the small had the percentage of clods of clay within the limit of the norm, among the small recycled none could meet the requirements. ARMB1 exceeded the limit by 0.12%, in this case, since extrapolation was low, it is recommended to use the aggregate to add a certain proportion of natural aggregate in order to reduce clods of clay.

The ARMB2 and ARMD presented values in the order of 5 to 7 times greater than the acceptable one. The high values are explained by the fact that the two aggregates contain may brick fragments in their composition (verified in visual analysis), which after hydration for 24 hours as directed by NBR 7218:2010 [14] are easily untangle, other ceramic fragments, as tiles and floors do not present the problem concerning bricks. Both large recycled aggregates met the requirements.

Table 9. Clods of clay of the small and large aggregates

Small Aggregate	**Clods of Clay (%)** (arithmetic mean ± standard deviation)	**Requirements 15116:2004**	
		ARC	**ARM**
ANMI	0.89 ± 0.15		
ARMB1	2.12 ± 0.41		
ARMB2	13.80 ± 2.34		
ARMD	9.95 ± 1.46		
Large Aggregate		≤2	
ANGI	0.00 ± 0.00		
ARGB1	1.56 ± 0.33		
ARGB2	1.69 ± 0.39		
ARGD	1.77 ± 0.13		

3.7 Specific mass and apparent specific mass

NBR 15116:2004 [18] does not use the specific mass and apparent specific mass as parameters of quality of the aggregates, however it was necessary to incorporate such properties in the studies, since the characteristics have great influence on the behavior of concrete produced. Recycled aggregates with densities close to those of natural aggregates tend to present better mechanical resistance in the final concrete.

The tests of specific mass and apparent specific mass were determined by standards NBR NM 52:2009 [16] (Small Aggregate-Determination of specific mass and apparent specific mass) and NBR NM 53:2009 [12] (Large Aggregate-Determination of specific mass, apparent specific mass and water absorption), the results are set forth in Table 10.

Table 10. Specific mass and apparent specific mass of small and large aggregates

Small Aggregate	Specific Mass (g/cm^3) (arithmetic mean ± standard deviation)	Apparent Specific Mass (g/cm^3) (arithmetic mean ± standard deviation)
ANMI	2.55 ± 0.02	2.62 ± 0.03
ARMB1	2.25 ± 0.03	2.44 ± 0.03
ARMB2	2.18 ± 0.01	2.45 ± 0.01
ARMD	2.12 ± 0.05	2.36 ± 0.01
Large Aggregate		
ANGI	2.99 ± 0.00	3.02 ± 0.01
ARGB1	2.41 ± 0.06	2.57 ± 0.05
ARGB2	2.31 ± 0.04	2.47 ± 0.04
ARGD	2.38 ± 0.01	2.53 ± 0.02

It is observed in the small aggregates that the highest specific and apparent mass index was the ANMI, as expected. Analyzing only small-recycled materials, it is possible to note a low variability in ARMB1 and ARMB2, both from the same plant, but collected at different periods, with relative heterogeneity of made aggregates. The ARMD proved to be the least dense of all small aggregates.

In the large aggregates, the natural (ANGI) presented the highest specific and apparent mass, and ARGB1 and ARGD, although they were from different plants, obtained very close values. ARB2, although belonging to the same ARGB1 plant, was shown to be not so close to the first collection.

Recycled aggregates with specific mass higher than 2.2 g/cm^3, have high levels of rocks, resulting in concrete with mechanical behavior similar to those produced with natural aggregates [22]. It is verified that all samples of recycled aggregates, except ARMB2 and ARMD, presented values higher than 2.2 g/cm^3, therefore, they are theoretically able to offer good values of mechanical resistance to concretes.

3.8 Crush resistance

The test for determination of crush resistance is determined only for large aggregates according to NBR 9938:2013. The test is not required by NBR 15116:2004 [8]; however, it was carried out to obtain the resistance of the recycled grains compared to the natural one. The results are shown in Table 11.

The lower the percentage of crush resistance, the smaller the amount of crushed sample, that is, the higher the resistance of the aggregate. Thus, the ANGI of diabetic rock origin had higher resistance; the recycled aggregates obtained smaller values, possibly because they have a higher void index (porosity), which interferes directly with the mechanical resistance. By analyzing the variability of the recycled aggregates exposed to the test, it can be observed that their values are very similar, even if they come from different sources.

Table 11. Large-recycled aggregates crushing resistance

Large Aggregate	Crush Resistance (%) (single determination)
ANGI	15
ARGB1	24
ARGB2	25
ARGD	24

In another study, the stone aggregate was used as a concrete aggregate for the stone aggregate following technical standards, among them NBR 9938:2013 [17], where the material reached a 33.4% resistance to crushing. Subsequently, the aggregate obtained from marble residues was used to shape test specimens, with different simulations of concrete dosages and with variations of the small and large aggregates, both from residues. Finally, after the curing period, the test specimens were tested at 7, 14 and 28 days for uniaxial compression, independent of the simulation characteristics, the concrete produced had similar strength and around 35 MPa which shows that the aggregate is suitable for use in concrete [23].

The material tested in the above mentioned study, which was used in the preparation of test specimens, reached excellent values of uniaxial resistance, being considered suitable for concrete use. The material had a crushing resistance of 33.4%, a lower value when compared to recycled aggregates (ARGB1, ARGB2 and ARGD), which was 24% and 25%. Thus, an indirect analysis involving the property of resistance of the aggregate to the crushing with the one uniaxial resistance that the aggregate provides to the concrete, that the ARGB1, ARGB2 and ARGD demonstrate suitable to provide good values of concrete resistance in the future produced.

4. CONCLUSION

In order to compile the information about the characteristics obtained from the recycled aggregates with the requirements of NBR 15116:2004 [8], Table 12 shows the recycled aggregates –small and large- and the tested attributes exposed by the standard.

For a recycled aggregate to be suitable for use on concrete without structural function, it is essential that its attributes meet the limits specified by NBR 15116:2004 [8]. None of the recycled aggregates fulfilled all the requirements, therefore all were rejected for this destination.

There were four attributes that aggregates were reproved, particle size, for one small and all large, non-mineral materials for one small, and clods of clay and consequently maximum contaminant content for all small.

As for the granulometric composition, the problems are not serious, since for the small a simple correction with addition of sand in the use of the aggregate could already be enough. Regarding the disapproved grains, it is recommended a redesign of the sieves in the recycling plants, since they are not attending to the granulometric areas required by norm or when a small strip outside the normalized area does not fit, it is advisable to add standardized gravel, and this resource may be enough.

Table 12. Meeting the requirements of NBR 15116:2004 by small and large recycled aggregates

Attributes	ARMB1	ARMB2	ARMD	ARGB1	ARGB2	ARGD
Granulometric composition	✓	×	✓	×	×	×
Water absorption	✓	✓	✓	✓	✓	✓
Chlorides	✓	✓	✓	✓	✓	✓
Sulfates	✓	✓	✓	✓	✓	✓
Non-mineral materials	✓	✓	×	✓	✓	✓
Clods of clay	×	×	×	✓	✓	✓
Maximum contaminant content*	×	×	×	✓	✓	✓
Fines	✓	✓	✓	✓	✓	✓

*) Sum of chlorides, sulfates, non-mineral materials and clods of clay. NBR 15116:2004 says that the sum should not exceed 3%.

In the case of clods of clay, it was observed that the cause of high clay content in small-recycled aggregates were from brick fragments, thus, it is suggested the exclusion of bricks from the productive process of the small aggregate destined to the preparation of concrete, removing them in the screening process. This suggestion is made only to the small ones, since large ones even containing a certain amount of bricks in the composition did not demonstrate the same problem.

For the small ones also it is recommended besides that the exclusion of bricks in the triage, the exclusion of bitumen, as observed, this component is vital for the recycled aggregate does not fit in the aspect non-mineral materials.

Comparing the recycled aggregates with the natural ones, it was verified that the recycled ones presented a higher index of fines and mainly greater absorption of water, which reflects in smaller values of specific mass, apparent specific mass and resistance to crushing. However, these are not limiting factors in the use of recycled in concretes without structural function, since they will not be so demanded mechanically.

However, even the recycled ones presenting lower resistance values than the natural one, through indirect analysis it is concluded that the values are possibly enough to provide good indexes of uniaxial resistance to the concrete. Therefore, specific studies on the resistance of concrete produced with recycled aggregates are necessary to enable the use of the recycled aggregate in more noble purposes.

Even the recycled aggregates showing some variability throughout the tests and not complying with some normative requirements, it is concluded that their use in concretes is close to becoming viable. Through the samples tested, it was verified that simple corrections in the recycling plants or additions of a certain amount of natural aggregate could already be sufficient for the total regulation of the recycled aggregate.

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