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Concrete produced with recycled aggregates

Concreto produzido com agregados reciclado

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Abstract

This paper presents the analysis of the mechanical and durable properties of recycled aggregate concrete (RAC) for using in concrete. The porosity of recycled coarse aggregates is known to influence the fresh and hardened concrete properties and these properties are related to the specific mass of the recycled coarse aggregates, which directly influences the mechanical properties of the concrete. The recycled aggregates were obtained from construction and demolition wastes (CDW), which were divided into recycled sand (fine) and coarse aggregates. Besides this, a recycled coarse aggregate of a specific mass with a greater density was obtained by mixing the recycled aggregates of the CDW with the recycled aggregates of concrete wastes (CW). The concrete was produced in laboratory by combining three water-cement ratios, the ratios were used in agreement with NBR 6118 for structural concretes, with each recycled coarse aggregates and recycled sand or river sand, and the reference concrete was produced with natural aggregates. It was observed that recycled aggregates can be used in concrete with properties for structural concrete. In general, the use of recycled coarse aggregate in combination with recycled sand did not provide good results; but when the less porous was used, or the recycled coarse aggregate of a specific mass with a greater density, the properties of the concrete showed better results. Some RAC reached bigger strengths than the reference concrete.

Keywords: recycled aggregate, specific mass, concrete, properties.

Resumo

Este artigo apresenta as análises das propriedades mecânicas e de durabilidade de concreto com agregados reciclados (CAR) para em concreto. Sabe-se que a porosidade dos agregados reciclados influencia as propriedades frescas e endurecidas do concreto e estas propriedades estão relacionadas com a massa específica dos agregados graúdo reciclado, que diretamente influencia as propriedades mecânica do concreto. Os resíduos de construção e demolição (RCD), que deram origem aos agregados reciclados, foram separados em agregado miúdo e agregado graúdo. Também, um agregado graúdo reciclado de maior densidade foi obtido misturando o agregado reciclado do RCD com o agregado reciclado de resíduo de concreto (RC). Os concretos com agregados reciclados foram produzidos com três níveis de relação a/c, as razões foram usadas de acordo com a NBR 6118 para concretos estruturais, combinando-se cada agregado graúdo reciclado com o agregado miúdo reciclado e com uma areia natural. Concretos de referência também foram produzidos utilizando-se agregados naturais. Observou-se que CAR tem potencial para aplicação como concretos estruturais. Em termos gerais, o uso combinado dos agregados graúdos e miúdos reciclados não foi vantajoso, mas as propriedades dos CAR eram tanto melhores quanto maior a massa específica dos agregados graúdos reciclados. Alguns CAR chegaram a apresentar resistências mecânicas maiores que as de seus respectivos concretos de referência.

Palavras-chave: agregado reciclado, massa específica, concreto, propriedades.

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1. Introduction

The heterogeneity of the composition; the specific mass with lower density; the adhered mortar quality and the amount of adhered mortar and the variability of the properties are all important characteristics of recycled aggregates, which represent obstacles not only for their use as well as for the reliability of the same in concretes used in structural applications (Lovato et al. [1], Etxeberria et al. [2], Tabsh et al. [3], Kwan et al. [4], Cabral et al. [5]).

The consequences of these characteristics are observed in the recycled aggregates themselves. Their properties normally do not obey the norms commonly destined to natural aggregates (QUEBAUD et al. [6]); and in the recycled aggregate concretes (RAC) made with the same aggregates tend to give less work, be weaker, more deformed (smaller module of elasticity), more porous and more permeable (Tabsh et al. [3], Etxeberria et al. [2]). In the case of recycled aggregate concrete, more cement needs to be added to the concrete made of 100% of recycled aggregate in order to achieve the same workability and compressional strength as conventional concrete (Etxeberria et al. [2]).

In the aggregates, the porosity affects more of their properties (MEHTA and MONTEIRO [7]) and two of them reflect well their level of porosity and are of relatively easy determination: the water absorption and the specific mass. In the concrete, its strength, durability, shrinkage and permeability suffers direct influence from the number, type, size and distribution of pores present in the aggregates, cement paste and transition zone (BASHEER et al. [8]).

As outlined by Kou et al. [9], the porosity of recycled aggregate concrete (RAC) is normally higher than that of natural aggregate concrete (NAC) due to the adhered mortar present in the recycled aggregates. The porosity and the pore size distribution are the most important characteristics of the pore system of concrete which influences the penetration of external substances to the interior of the concrete. Therefore it is important to understand the development of the pore system in order to assess the durability properties of the recycled aggregate concrete.

Based on the criteria commonly related to the water absorption, specific mass or values of Los Ángeles abrasion, it is an important beginning given by the Science of Materials that is the existent inversely proportional relation between porosity and the mechanical strength of that material, valid in several materials and also in concrete and ceramic (MEHTA and MONTEIRO [7]).

Many studies, norms and recommendations have been proposed or established forms of classifying the recycled aggregate according to the percentage of each phase (concrete, mortar, ceramic etc.). With the intention of assuring a smaller variation of the phases, the norms and recommendations have defined criteria that must be obeyed with recycled aggregates (e.g. values of water absorption). The classification is usually made in visual form and the definition of the best phase begins with the selection of aggregates with stronger and more resistant materials (e.g. concrete), which are also more resistant and can be used in applications of larger importance. One of the reasons for which the concrete is seen as more resistant is because it has rocks.

The classification based on the visual criteria which is limited because of each phase of CDW has its own variability. For instance, it is possible to find concretes of different strengths produced with different water/cement (w/c) ratios, and different amounts of coarse aggregates, originated from rocks of different resistances. The studies of CARRIJO [10] and ANGLE [11] prove these facts.

The concrete properties with recycled coarse aggregate of CDW, separated by specific mass, showed a larger relation with the density rather than with the visual criteria called "grey aggregate" or "red aggregate", demonstrating the fallibility of the visual classification system. The density separation (d) done by CARRIJO [10] was based on the specific mass of the aggregates or, in other words, each aggregate inside a certain order of specific mass ($d < 1.9\ kg/dm^3$, $1.9\ kg/dm^3 < d < 2.2\ kg/dm^3$, $2.2\ kg/dm^3 < d < 2.5\ kg/dm^3$ e $d > 2.5\ kg/dm^3$) has grains with specific mass of that order so that its denser aggregates, for instance, a great part of them are grains of rock. The concrete showed improvement in its properties (compressive strength, elasticity module, etc.) with the increase of the specific mass of the recycled aggregates. The compressive strength of the recycled aggregate concrete (RAC) was less resistances in comparison to the conventional concrete, and decreased as the density of the aggregates decreased. However, concrete made with aggregates of density ranges between $d > 2.5\ kg/dm^3$ and $2.2\ kg/dm^3 < d < 2.5\ kg/dm^3$ showed resistance values close to those of conventional concrete. Furthermore, the RAC obey the Abrams Law.

1.1 Objectives

An experimental study was developed in order to evaluate the mechanical and durable concrete properties produced with recycled coarse aggregates from different specific mass and compared to those obtained with natural aggregates with the possible objective of obtaining recycled aggregate concretes (RAC) appropriate for applications in concrete with properties to structural concrete.

2. Materials and experimental program

2.1 Material

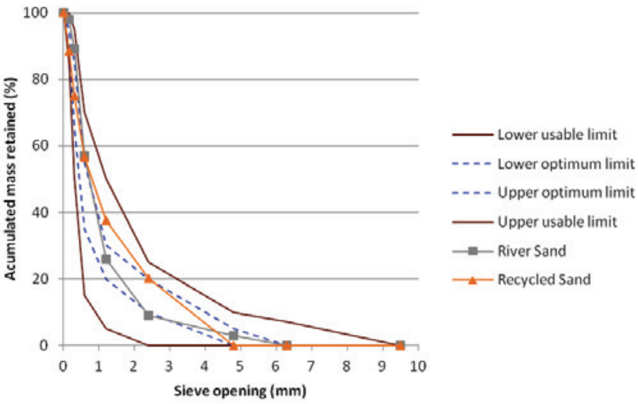
Samples of mineral fraction from the CDW were obtained from around the city of Maceió and from the CW of the Laboratory of Structures and Materials (LSM) of the Federal University of

Figure 1 – Recycled coarse aggregates composition

Table 1 – Fine aggregate properties

Property	River sand	Recycled sand	Standard procedure
Water absorption (%)	1.22	9.34	NBR NM 30 (12)
Density (kg/dm³)	2.68	2.50	NBR 9776 (13)
% organic matter (ppm)	< 300	< 300	NBR NM 49 (14)
% particles with D<0,075 mm	1.00	8.61	NBR NM 46 (15)
Dmax (mm)	4.75	4.75	–
Fineness modulus	2.82	2.78	NBR 248 (16)
Grading zone	Usable	Usable	–

Figure 2 – Granulometric curves of fine aggregates and limits (NBR NM 248:2003)



Alagoas. Both the recycled sand and coarse aggregates were obtained by the reduction process in a mill of hammers. The figure 1 shows the composition of the recycled coarse aggregates from the CDW.

The naturally fine aggregate used was natural river sand, but the recycled sand aggregate was from the mineral fraction of CDW obtained in a mill of hammers, sieved in a 4.75 mm sieve. The properties of the fine aggregates are shown in table 1 and figure 2.

The natural coarse aggregate used was crushed stone of the maximum of 19 mm in diameter, typically used in the city. There were two types of recycled coarse aggregates: the first from CDW (called G1), figure 3a, and the other from the mixture of G1 with the CW (called G2), figure 3b. Both aggregates were sieved in a 25.4 mm sieve and were predominantly retained in the 4.75 mm sieve.

The specific mass of G2 was defined based on the studies of CARRIJO [10] and ANGLE [11]. In their studies, the specific mass average of the aggregate particles was formed by mixing particles of different materials (mortar, rock, ceramic etc.), each one with a different specific mass.

The amounts of CDW and CW aggregates were calculated by an equation system formed by the equations 1 and 2 listed below. The

Figure 3 – Recycled aggregate: (a) G1 and (b) G2

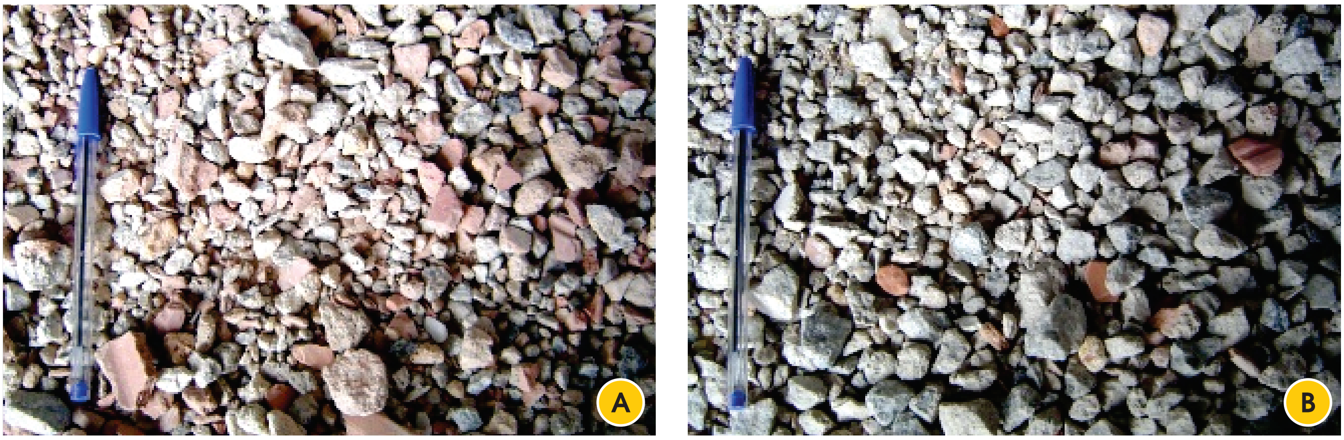
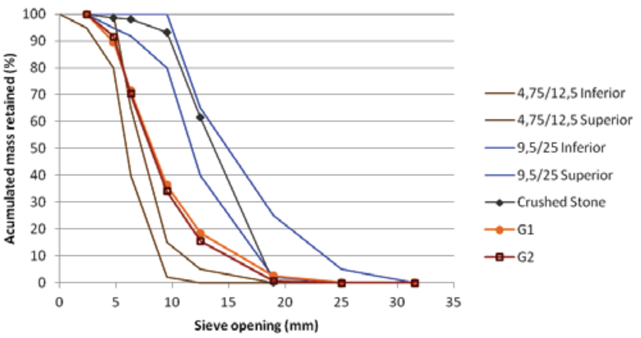


Figure 4 – Granulometric curves of coarse aggregates and limits (NBR NM 248:2003)



first is a formulation that relates the specific mass of each aggregate and the second is a relation by mixing two materials.

$$\%M_{G1}\cdot\gamma_{G1} + \%M_{CWA}\cdot\gamma_{CWA} = \gamma_{G2} \tag{1}$$

$$\%M_{G1} + \%M_{CWA} = 1 \tag{2}$$

In the equations 1 and 2, %MG1 is G1's coarse aggregate percentage in mass; γG1 is the specific mass of G1's coarse aggregate; %MCWA is CW's coarse aggregate percentage in mass; γCWA is the specific mass of CW's coarse aggregate and γG2 is the specific mass of the mixture or, in other words, G2's coarse aggregate. The resolution of the system of equations above with the adequate values of specific mass resulted in %MG1 = 22.74 and %MCWA = 77.26. The coarse aggregate properties are shown in table 2 and figure 4.

The cement used was composed by Portland CPII-F-32. A 3rd generation superplasticizer based on an ether-modified carboxylic chain was used to used to assure an appropriate consistency to the concrete. The water used was the water available in the laboratory's water system.

2.2 Mix design

The composition parameters of the concrete taken as independent variables in this study were:

- Effective water-cement ratios: 0.67, 0.50 and 0.40 were determined fixing the used in agreement with NBR 6118 [20] for structural concretes;
- The specific mass of the recycled coarse aggregate: 2.08 kg/dm³ for G1 and 2.27 kg/dm³ for G2;
- Fine aggregate: natural sand and recycled fine aggregate of CDW.

The compositions obtained for the combination of the parameters and reference mixtures are shown in Table 3. The water was fixed at 20% of 1 m3 (200 kg) and cement dosage at 300, 400 and 500 kg/m3. The method of mixing did not follow any commonly used method. The amount of coarse aggregate was fixed at 40% for all the mixtures; this percentage was determined previous to the normal mixture with a mortar content of 50%. First, the form of mixing of the reference concrete was determined in volume and only the mixtures of RAC were calculated. This was done so that the difference between the specific mass of the natural and recycled aggregates did not lead the production of different concrete volumes.

2.3 Production

According to FERREIRA [21] the reducing of the effective w/c ratio of the mix can to be overcome if the water absorbed by the recycled aggregates is compensated or by extra water added to the mix or by the recycled aggregates pre-saturated added to the

Table 2 – Coarse aggregate properties

Property	Brita(1)	G1	G2	Standard procedure
Water absorption (%)	0.49	8.41	5.37	NBR NM 53 (17)
Specific mass (kg/dm³)	2.62	2.08	2.27(2)	NBR NM 53 (17)
Index of particle shape	2.60	2.30	2.20	NBR 7809 (18)
% particles with D< 0.075 mm(3)	0.33	0.75	0.45	NBR NM 46 (15)
Dmáx (mm)	19.0	19.0	19.0	–
Fineness modulus	6.86	5.76	5.85	NBR 248 (16)
Grading zone	9.5/25	None	None	–

(1) - Crushed stone coarse aggregate; (2) - The intended value was 2.25 kg/m³ (which was used in Equation 1). The experimentally obtained value was 2.27 kg/m³; (3) - using NBR 7219 (19).

Table 3 – Concrete mixtures

Mix(*)	Effective w/c ratio	Materials in volume $(dm^3)/m^3$				Materials in mass $(kg)/m^3$			
		water	cement	Aggregate		water	cement	Aggregate	
				Fine	coarse			fine	coarse
67MRG1	0.67	200	99	301	400	200	300	752.5	832
67MRG2	0.67	200	99	301	400	200	300	752.5	900
67MNG1	0.67	200	99	301	400	200	300	806.7	832
67MNG2	0.67	200	99	301	400	200	300	806.7	900
50MRG1	0.50	200	132	268	400	200	400	670.0	832
50MRG2	0.50	200	132	268	400	200	400	670.0	900
50MNG1	0.50	200	132	268	400	200	400	718.2	832
50MNG2	0.50	200	132	268	400	200	400	718.2	900
40MRG1	0.40	200	165	235	400	200	500	587.5	832
40MRG2	0.40	200	165	235	400	200	500	587.5	900
40MNG1	0.40	200	165	235	400	200	500	629.8	832
40MNG2	0.40	200	165	235	400	200	500	629.8	900
Reference concrete (Ref)									
Ref67	0.67	200	99	301	400	200	300	806.7	1048
Ref50	0.50	200	132	268	400	200	400	718.2	1048
Ref40	0.40	200	165	235	400	200	500	629.8	1048

(*) 67, 50 and 40 refer to effective w/c ratio; MR = recycled sand; MN = river sand; G1 and G2 = recycled coarse aggregates.

mix. Therefore, the recycled aggregates (fine and coarse) were pre-soaked in mixer for one minute before the preparation of the concrete to avoid the absorption of part of the mixture water. The quantity of this water was calculated with the difference between the water required for the full saturation of the aggregates and the water actually absorbed by the aggregates in one minute. The absorption of 70% of the total water absorbed by each aggregate had already been observed in one minute.

The superplasticizer was used for a plastic consistence to be reached.

The preparation of the concrete was: 1 - Reference concrete: coarse and fine aggregates, and a little of water mixed for one minute in a mixer. 2 - Recycled concrete: recycled coarse and fine aggregates, and absorbed water from the recycled aggregates (70%) mixed for one minutes in a mixer. Afterwards, the cement and the water of the mix are placed in the mixer for two minutes. At the end, the superplasticizer was mixed for one minute and a half more.

After casting, the samples (cylinders with 10 cm in diameter and 15 cm in height) were led in molds for 24 hours, stripped and cured in water for twenty-eight days. All concrete cylinders were capped with a thin layer of sulfur with cement to ensure the smoothness of the top surface.

2.4 Properties and test

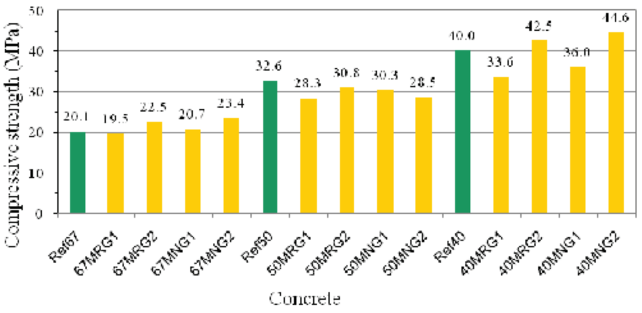
The compressive strength, water absorption, air content and time of air-permeability (Figg method) properties were obtained with the intention of analyzing the possibility of producing concretes with recycled aggregates. For each concrete, the tests were made in cylinders of 100 mm in diameter and 200 mm in height; three specimen for the compressive strength (NBR 5739 [22]), three for the water absorption and air content (NBR 9778 [23]). For the measurement of the air-permeability time (LNEC-E 413 [24]), a prismatic mold of 15x15x30 cm was used with 5 holes of 6 mm in diameter and 40 mm in height were made. The reference age for the accomplishment of the tests was 28 days. The adopted cure method for all the concretes was the total immersion of the specimens in water.

3. Results and discussions

3.1 Aggregate Properties

The results obtained from the recycled aggregate properties: water absorption and particles percentage with D < 0.075 mm, which obeyed the minimum requirements defined by the NBR 15116

Figure 5 – The Concrete's compressive strength



[25]. The higher water absorption of recycled aggregates was influenced by the presence of constituents red aggregate, which also they influenced the specific mass.

In the figure 2, the content of fine and powdered materials is observed to be higher in recycled sand, however, the recycled sand demonstrated to be thicker than river sand, and could fit in the grading zone used for natural fine aggregate. In figure 4, the recycled coarse aggregates (G1 and G2) are observed to have similar granulometries and which do not fit in granulometric zones of the standard.

3.2 Compressive strength

Figure 5 shows the average of the results for the compressive strength tests (fc) in samples.

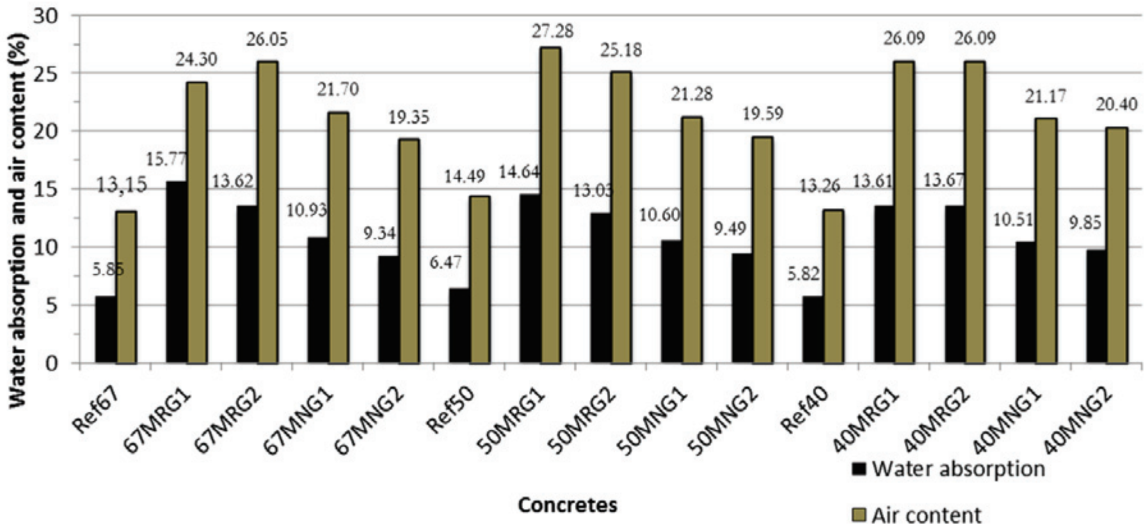
In figure 5, it is possible to notice how the concrete, independent of the aggregate type and specific mass of the recycled coarse aggregate, obey the Abrams law, i.e., a higher w/c ratio corresponds to a lower compressive strength, and in general, the RAC showed compressive strength near the reference concrete. The accentuated reductions of the strengths become evident to the negative influence of the recycled aggregate G1, CDW origin and lower specific mass, on the compressive strength of the concrete. The strength values which were equaled or overcame the strengths of the reference concrete were of the concrete with recycled G2 aggregate, mixing G1 with CW, with larger density. In general, the recycled aggregate concrete with larger specific mass (G2) had compressive strength greater than those of concrete with recycled aggregates of lower specific mass. And when w/c = 0.40 and 0.67, the compressive strength of these concretes is also higher than those of the concrete with natural aggregates.

The strengths of 19.0 MPa < fc < 23.5 MPa of the RAC with w/c = 0.67 were similar to the reference concrete. This displays that the recycled aggregate and its characteristics (composition and specific mass) were not the decisive factors for the strength, but the high w/c ratio, which did with that the paste and the transition zone governed the strength. According to NEVILLE [26], the paste becomes a more and more limiting factor of the strength with the increase of the w/c ratio, which was also verified by CARRIJO [10]. Another justification is that the recycled aggregate could have absorbed part of the water mixture, reducing the effective of the w/c ratio of the concrete and increasing its strengths. LEITE [27] and VIEIRA [28] also observed that behavior to high w/c ratio. Whereas for concrete with w/c = 0.50 and the strength of 28.0 MPa < fc < 33.0 MPa, RAC showed values of lower strength than the reference concrete, in this case, the recycled aggregate can be considered to be the limiting factor to the strength. For concretes with w/c = 0.40 and strength in the range 33.5 MPa < fc < 45.0 MPa, the influence of the aggregate type in the strength of the concretes is more evident. The concrete

Table 4 – Rupture aspect of the recycled aggregates

Concrete	Type of recycled aggregates that appeared in the specimens
67MRG1	Non-rock grains + rock and non-rock grains detached
67MRG2	Non-rock grains + rock grains detached
67MNG1	Non rock grains
67MNG2	Non-rock grains and some rock grains
50MRG1	Non-rock grains
50MRG2	Non-rock and some rock grains
50MNG1	Non-rock grains
50MNG2	Rock e non-rock grains
40MRG1	Rock e non-rock grains
40MRG2	Rock and non-rock grains + a few detached rock grains
40MNG1	Non-rock + some detached rock grains
40MNG2	Rock and non-rock aggregates

Figure 6 – Water absorption and air content of the concretes



with recycled aggregates, type G1, showed lower resistances than the reference concrete, which shows their limitation, whereas concrete with G2 showed superior strength to the reference concrete. The G2 aggregate showed smaller particles than the natural aggregates, which collaborates enough to provide a stronger transition zone, but besides the difference between the superficial texture and larger porosity of G2 in relation to the natural aggregates, allowed a larger adherence to the paste, which helped the concrete with G2 to overcome the strength of the reference concrete. Table 4 shows the aspect of the rupture of the samples of the RAC.

The concretes with recycled fine aggregates showed smaller resistances in relation to the concrete with natural sand. In general, the compressive strength obtained by the concrete agrees with NBR 6118 [20] in structural concretes.

The related aspects with the rupture and detachment of the coarse aggregate are shown in table 4. They also confirm that which was mentioned in terms of the resistance of the concrete when the w/c ratio is altered. For the w/c = 0.67, the rupture happened predominantly in the non-rocky aggregates (ceramic and mortars) which have low resistance and, probably, similar strength to the paste. The rocky aggregates, just as if detached, prove the weakness of the transition zone. For the w/c = 0.4, there was also some rupture in the rocky aggregates, which showed that in these cases the paste was more resistant. The concrete of w/c = 0.5 showed an intermediate behavior.

Figure 7 – Air-permeability time of the concretes

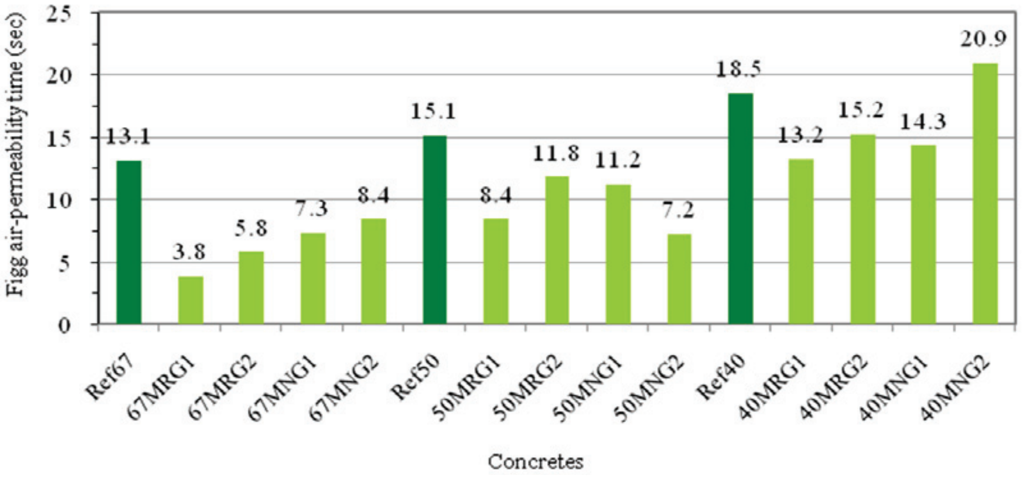
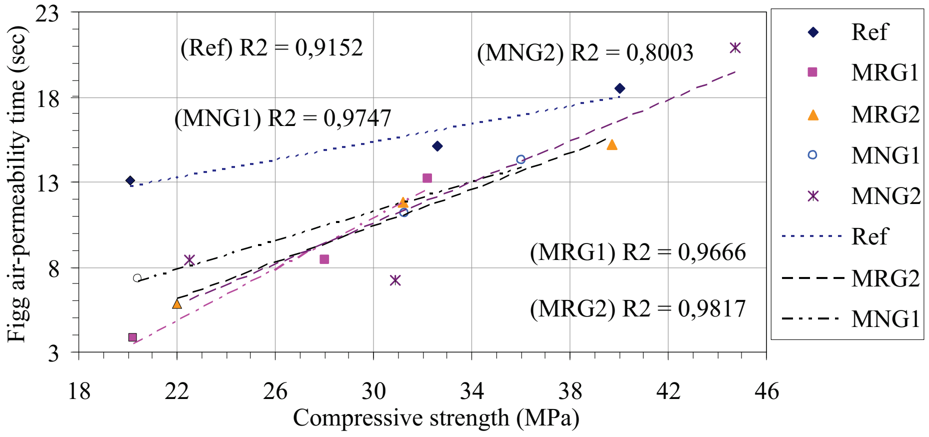


Figure 8 – Air-permeability time in function of concrete compressive strength



3.3 *Water absorption, air content and air-permeability time*

The results of water absorption and air content are shown in figure 6, and the results of the air-permeability time are shown in figure 7. In figure 6, the RAC generally has a larger absorption and a larger air content than the reference concrete, demonstrating that the recycled aggregate negatively influences the porosity of the composite. It is also possible to notice a normal tendency of decrease in the water absorption and in the air content when moving from the recycled fine aggregate to the sand and of the coarse aggregate G1 to G2, that is, when less porous aggregate is used in the concrete. On the other hand, so much for the RAC as for the reference concrete, the two properties seemed not to be sensitive to the alteration of the w/c ratio. Noticed that any concrete with similar composition (for instance xxMNG1) had an absorption value or an air content very similar to the three studied w/c ratios. Therefore demonstrating that in any concrete, the absence of a clear relation inversely proportional between the porosity of the material and its compressive strength. It is still observed the fact that the tests they give indications (figure 6) that they are not sensitive, or they are little sensitive, to the alterations of the w/c ratio.

In figure 7, the property air-permeability time of the RAC was sensitive to the changes in the types of aggregates, it also happened with the water absorption and the air content. The test, unlike the absorption and of the air content, measuring the air-permeability time was sensitive to the alteration of the w/c ratio, decreasing as this increased, and to the aggregate type, increasing when the fine aggregate is normal and the recycled coarse aggregate is G2. The relation between the permeability and compressive strength of the concretes can be seen in the figure 8, in which, for each concrete, each point corresponds to a w/c ratio.

In figure 8, the air-permeability time demonstrated a relation with the compressive strength of the concrete, the larger the air-permeability time the larger the resistance to the concrete. The concretes tended to be more resistant the smaller the permeability, confirming that for this composite, independent of the type of aggregate used. The relation between porosity and resistance is valid proven by the Science of the Materials. Part of the porosity of the RAC might have been caused by the migration of part of the water pre-soaked of the aggregates recycled for the paste.

4. Conclusions

This study developed the following final considerations:

- The composition and properties of the recycled aggregates influence on the production and in the fresh and hardened properties. In the mixture, the absorbed water from the aggregates needs to be controlled; and the density of the recycled coarse aggregate may be a parameter for selection of recycled aggregates with structural purpose.
- The values of the strength obtained were inside of the structural concrete norms and specified in the Brazilian norm for the calculation of structures of armed concrete.
- The compressive strength of the RAC was approximately 20 MPa for the w/c = 0.67, the strength was approximately 30 MPa for the w/c = 0.50 and was approximately 40 MPa for the smallest w/c = 0.40. This behavior happened independently from the type of aggregate used, and therefore shows that all concretes obeyed the Abrams Law, which is with the increase of the relation, the compressive strength is decreased.
- The properties of compressive strength and those related to the durability of the concretes generally showed better performance in the concretes with recycled coarse aggregate of larger density (G2), compared to the concretes with recycled aggregate of smaller density (G1) independent of the type of fine aggregate.
- The concretes with recycled fine aggregate normally had their properties inferior to the one of the concretes with natural fine aggregate.
- The RAC were more porous and permeated than the conventional concretes, with exception to the 40MNG2 concrete which refers to the permeability. The more porous concretes and permeated, tend to be less durable for providing, in the case of the applications structural, smaller protection to the steel against external aggressive agents that can penetrate the composite.

However, that will only come to be extremely a limiting factor to the use of those concretes in the case of those structures in that the same ones are apparent. The Brazilian Norm of project reinforced concrete structures mentions that coatings can be applied on the concrete in the intention of protecting the material of the noxious environmental conditions.

- The concrete properties were revealed sensitive to the decrease of the porosity of the recycled coarse aggregate so that the values of these tended, in some cases, to be very close or until overcoming the values of the properties of the conventional concretes.

Based on the results found in this study for the RAC properties, it seems possible the use of this material in structural elements since observed their particularities and other mechanical properties, dimensional and of durable, which can come to be factors limits in some structural applications. Furthermore, in the case of application in structures, testing for verification of contaminants in the recycled aggregates must be performed in order to avoid possible pathologies.

The results reached in the concretes with recycled aggregate of larger density showed that the aggregate's density, which is related to the resistance and porosity of the same, and that had a great influence in the obtained concrete properties. Therefore, this property can be a decisive factor for obtaining structural concretes.

5. Acknowledgements

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