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MECHANICAL AND PHYSICAL PROPERTIES OF RECYCLED AGGREGATES CONCRETE

PROPRIEDADES MECÂNICAS E FÍSICAS DOCONCRETO COM AGREGADOS DE RESÍDUOS DE CONCRETO

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Abstract: Aggregate type - natural or recycled - governs a range of concrete properties (e.g. water absorption and workability).Knowing this, there are many recommended mixing methods for maintaining concrete workability.However, they may be not economic feasibleor they maydepreciate mechanical properties. In this work, four concrete mixtures were produced replacing 0, 30, 50 and 100% of natural coarse aggregates by recycled concrete aggregates without any pre-wetting method or additional water. Instead of, the "Two-Stage Mixing Approach" mixing method was used. From the experimental tests it was possible to observe the influence of the substitution content on the workability, water absorption ability, density, voids index, compressive strength, tensile strength and modulus of elasticity.In addition, the tensile strength and elastic modulus values of recycled concrete were also compared to those obtained in the equations recommended byABNT NBR 6118:2014 for concrete with natural aggregates. The results showed that it is possible to maintain the workability of concrete without depreciating its mechanical properties.

Keywords: recycled concrete, recycled concrete aggregates, mixing method, workability, mechanical properties.

Resumo: *O tipo de agregado - natural ou reciclado – é responsável por uma série de propriedades do concreto (ex: absorção de água e trabalhabilidade).Sabendo disso, existem muitos métodos de mistura recomendados para manter a trabalhabilidade do concreto. No entanto, eles podem não sereconomicamente viáveis ou podem depreciar as propriedades mecânicas. Neste trabalho, quatro traços de concreto foram produzidos substituindo 0, 30, 50 e 100% dos agregados naturais graúdos por agregados de resíduos de concretosem nenhum método de pré-molhagem ou adição de água extra. Ao invés disso, foi utilizado o método de mistura denominado "Two-StageMixing Approach". A partir dos ensaios experimentais foi possível observar a influência do teor de substituição na trabalhabilidade, absorção do concreto, massa específica, índice de vazios, resistência à compressão, resistência à tração e módulo de elasticidade.Além disso, os valores de resistência à tração e módulo de elasticidade do concreto reciclado também foram comparados aos obtidos nas equações recomendadas pela ABNT NBR 6118:2014 para concreto com agregados naturais. Os resultados mostraram que é possível manter a trabalhabilidade do concreto sem diminuir as suas propriedades mecânicas.*
Palavras-chaves:*concreto reciclado, agregados de resíduos de concreto, método de mistura, trabalhabilidade, propriedades mecânicas.*

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1 Introduction

The concrete is a mixture of primary ingredients as cement, aggregates (fine and coarse), water and admixtures and it is one of the construction materials that more consume the natural resources. In order to mitigate the environmental impact of civil construction, research focusing on concrete recycling has highlighted in the last two decades. There are many types of materials that can be recycled and used as a substitute for natural aggregates in concrete. For examples concrete, brick, ceramic, rubber, glass, etc.(VERIAN; ASHRAF; CAO, 2018).

The use of concrete waste as aggregates of new structural concrete is already includedin many standard codes around the world, such as the Netherlands (CUR-VB1984), Germany (DIN 4226-100:2002), Switzerland (Ot 70085:2006), Hong Kong (WBTC 12:2002), Portugal (LNEC E 471:2009) andUnited Kingdom (BS 8500-2:2006). In Germany and Switzerland there are a lot of examples of use of recycled concrete aggregates (RCA) in new construction, and, this technology is also already present in other countries. In contrast, while there is a record in 2018 of the collection of 122,012 tons of construction and demolition waste in Brazil (ABRELPE, 2019), the Brazilian standard codes do not yet provide the use of this waste for structural purposes. The Brazilian standard (ABNT NBR 15116:2004) that deals with concrete with RCD aggregates was published only in 2004 with the use requirements of these aggregates in paving and concrete without structural functions.

Recycled concrete aggregates (RCAs) have specific properties that result in some differences in relation to conventional concrete. When old concrete is crushed, a certain amount of mortar and cement paste from the original concrete remains attached to stone particles in the recycled aggregate. Compared to natural aggregates, RCA besides having higher water absorption and heterogeneity in composition presents lower mechanical strength due to the presence of old adhered mortar.

It can be stated that the high water absorption ability of recycled aggregates influences the workability since the recycled aggregates absorb water from the mixture (FERREIRA; DE BRITO; BARRA, 2011). Due to the higher porosity and absorption of recycled aggregates compared to natural aggregates (NA), different recommendations are found in the literature for the concrete production process using RCA. The Brazilian standard (ABNT NBR 15116: 2004) also recommends, for the recycled aggregatesconcrete without structural function, the pre-wetting of aggregates around 80% of the water absorption aggregates capacity.

In addition to controlling the amount of water added to the mixture on the speed and absorbability of the recycled aggregate, mentioned above, three recycled concrete mixing methods are most commonly used: first, pre-wetting with mixing water compensation (LEITE, 2001); second, the pre-wetting without adding extra water to the mixture, used by Moretti(2014)and the third one, the “Two-Stage Mixing Approach - TSMA” method proposed by Tam and Tam (2008). The three concrete mixing methods mentioned are illustrated in Figure 1.

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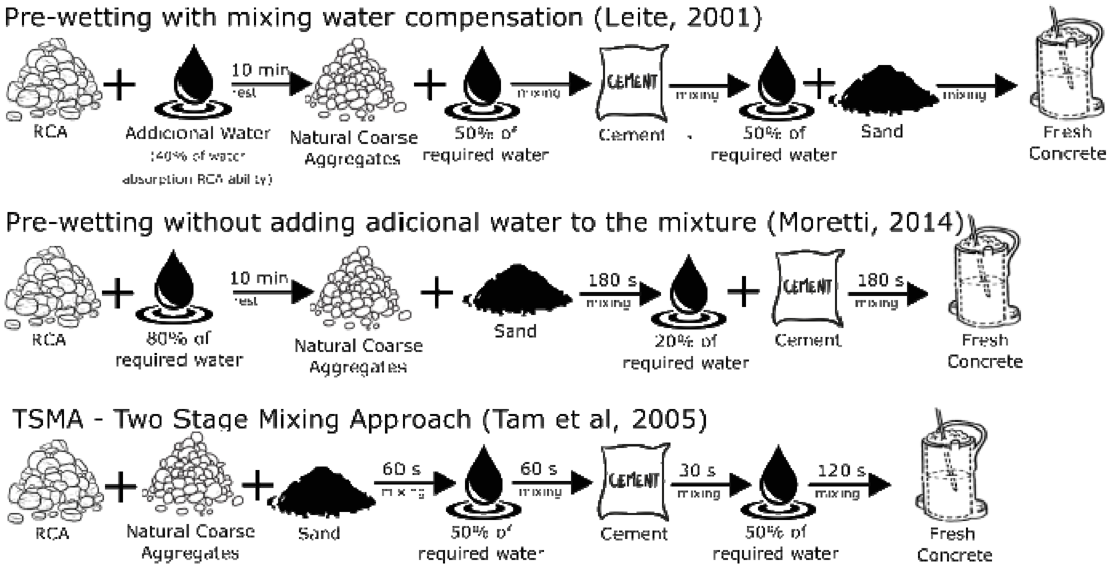

Figure 1. Mixing procedure of recycled concrete manufacturing

As the water absorption of recycled aggregate reduces considerably when RCA are semi-saturated, several studies (BUTLER; WEST; TIGHE, 2011; CABRAL, 2007; ETXEBERRIA et al., 2007; LEITE, 2001; MORETTI, 2014) recommend pre-wetting before mixing concrete. This procedure avoids the decrease of the freshconcreteworkability. However, as the aggregates are pre-wetted, the concrete strength decreases due to the increase of the effective water-cement ratio. The water/cement (w/c) ratio may be replaced by the effective water/cement ration when aggregates with high water absorption are used in concrete. The effective w/c ratio uses the total water amount minus the amount of water absorbed by the aggregates(MONTERO and LASERNA, 2017).The influence of the effective water/cement ration is higher with increasing replacement rate because more water is added to the mixture.

Etxeberria *et al.*, (2007) indicated thatrecycled aggregates should be pre-wetted, but not be saturated, as this can result in the failure of the effective interfacial transition zone (ITZ) between saturated recycled coarse aggregates and new cement paste. According to Mehta and Monteiro (2008), ITZ is considered the limit strength of concrete, it is due to this region that the concrete breaks at a lower stress than the strength of aggregates and cement paste. In addition, the characteristics of ITZdirectly influence on the elastic modulus of the concrete.To control the amount of water absorbed by the aggregate it is important to know the absorption rate of the recycled aggregate because the water absorption ability of RCA is very different from that of natural aggregates. Thewater absorption of the RCAis very intense in the first instants of water immersion, which means that RCA rapidly achieves a high humidity level(FERREIRA; DE BRITO; BARRA, 2011).The difficulty of this method is in controlling the absorption of a large amount of aggregatesfor practical engineering application.

The use of water reducing admixtures is proposed by Barbudo*et al.*(2013) to improve the workability and mechanical properties of recycled concrete.Water reducing admixtures decrease the need of adding water for the same slump, thereby decreasing the effective water/cement ratio and improving the concrete workability.On the other hand,this solution cannot be the best solution economically due the cost of water reducing admixtures.

As can be seen, several studies use methods as saturation, pre-wetting, mixing water compensation or other methods to reduce the absorbed mixing water by recycled

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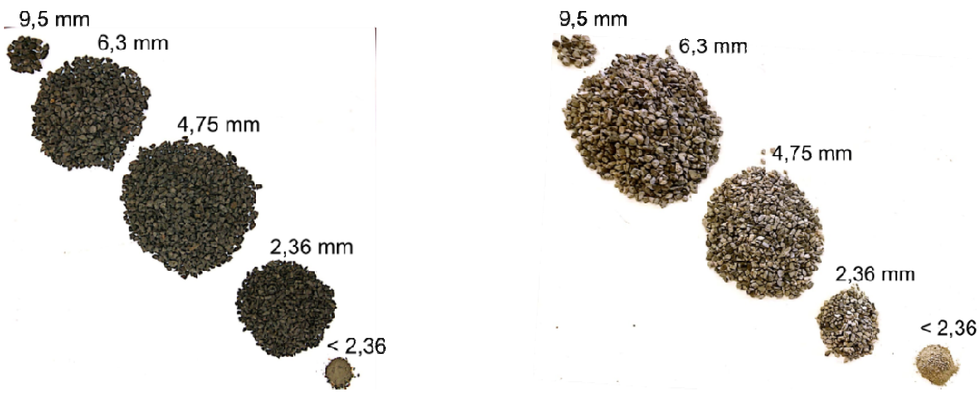
aggregates.However, these methods may not have practical and economic advantages.In the present study, the concrete mixtures were done without any of these methods to analyze the influence of the recycled coarse aggregates replacement rate on the mechanical and physical properties of recycled aggregates concrete (RAC).Concrete mixtures were produced using 0%, 30%, 50% and 100% of RCA on substitution of natural coarse aggregates.Since, it is known that replacing NCA by RCA decreases workability,a highly workable dosage (PEREIRA, 2017) was used.In addition, the "Two-Stage Mixing Approach" (TSMA) proposed by (TAM and TAM, 2008)was also used to prepare the concrete mixtures.

2 Characterization of Aggregates

In this study, cylindrical specimens of concrete measuring 100 × 200 mm (diameter × height) were collected from laboratory. The recycled aggregates were made by crushing of concrete samples in a jaw crusher. The gape of the jaw crusher has fixed size and it is not possible to adjust the size of the resulting generated aggregates. After the crushing the samples were sieved to obtain the fractions. For a valid comparison between both natural and recycled aggregates, the recycled aggregates were standardizes maintaining almost the same size distribution range as natural coarse aggregates. Thus, samples were standardized by sieving (meshes: 2.36mm, 4.75mm, 6.3 mm, 9.5mm, 12.5mm, 19mm and 25mm)tomaintain the same particle size distribution of the natural coarse aggregate (NCA). Natural coarse aggregates are original to crushed basalt stone. A general view of both NCAand RCA is in Figure 2. Natural sand with a fineness modulus of 1.91 was utilized as fine aggregate.The particle size distributions of NCA, RCA and natural sand weredetermined following the Brazilian standard (ABNT NBR 248:2003) and are shown in Figure 3.



a) Natural coarse aggregate b) Recycled coarse aggregate

Figure 2. General view of NCA and RCA

In addition to particle size distribution, the physical properties of aggregates were also determinedaccording of Brazilian standards. The results are shown in Table 1.

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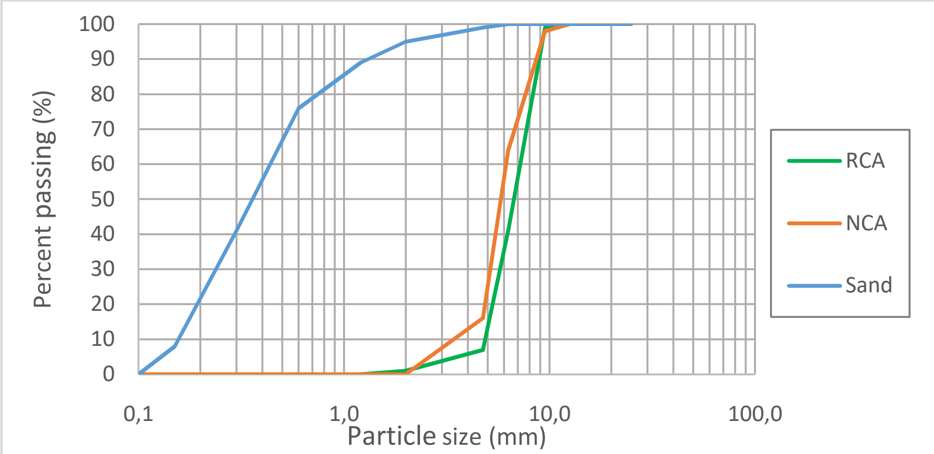

Figure 3. Particle size distribution of the natural and recycled aggregates

Table 1. Physical properties of fine and coarse aggregates

Properties	**Brazilian Standard codes**	**NCA**	**RCA**	**Sand**
Specific density (g/cm³)	ABNT NBR 53:2009	2.85	2.42	2.57
Water absorption (%)	ABNT NBR 53:2009	1.6	5.7 (+256.2%)	0.2
Maximum size aggregate (mm)	ABNT NBR 248:2003	9.5	9.5	2.4
Fineness modulus	ABNT NBR 248:2003	2.22	2.52	1.91

Since absorption is an extremely relevant factor for RCA, the absorption rate was determined using a method proposed by Leite (2001). This method consisted of submerging a predetermined amount of RCA in water and monitoring weight values during 24 hours. Thus, it was possible to obtain the RCA water content at each time period. The water absorption behavior of the RCA (Figure 4)can be divided in two phases: in the 1st phase occurs a quick rate absorption because the water is absorbed by the superficial larger pores. After, in the 2nd phaseas the absorption occurs in the deeper and smaller pores the rate absorption is slower (ECKERT and OLIVEIRA, 2017).According to the Figure 4, 50% of the water absorption occurs within the first 30 minutes. After this, the absorption becomes slower and the variation of the apparent weight can be negligible after 9 hours.

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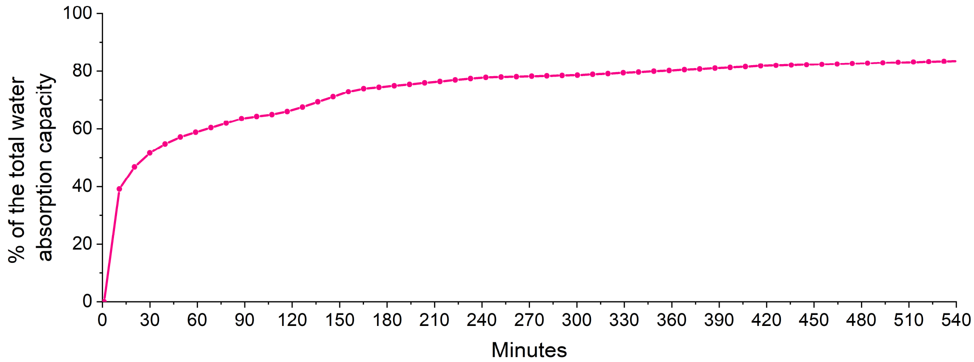

Figure 4. Aggregate water absorption in percentage of the total absorption capacity *versus* immersion time

3 Test programand mixing method

3.1 Mixing composition

The dosage was not the focus in this study. The reference dosage of the conventional concrete (natural aggregates) was developed by Pereira(2017) and the three other concrete mixtures were produced with the replacement in 30%, 50% and 100% of the NCA by ARC.

In this study was investigated the effects of these percentage replacement on both fresh and hardened properties of concretes. A total of four concrete mixtures were investigated in the present study. For this, four compositions were prepared, one of reference mix with NCA only, and three mix with different percentages of RCA. Concrete mixtures with recycled aggregates were evaluated considering three percentage replacement of coarse aggregate: 0%, 30%, 50% and 100%.

The replacement was performed according to NCA volume rather than the weight to maintain a similar total aggregate volume, same methodology used by(KUSTER JUNIOR, 2018; LEITE, 2001; MORETTI, 2014). This volume compensation is presented by Equation 1.

$$M_{RCA} = M_{NCA} \cdot \frac{d_{RCA}}{d_{NCA}} (1)$$

M_{RCA} =mass of recycled concreteaggregates (kg);
M_{NCA} = mass of natural coarse aggregates(kg);
D_{RCA} =density of recycled concreteaggregates (kg/dm³);
d_{NCA} = density of natural coarse aggregates (kg/dm³);

The recycled concrete mixtures were named as RAC-X (where X is the percentage replacement of coarse aggregate). The material proportions of the four concrete mixtures are listed in Table 2.

An early strength Portland cement CP-V ARI correspondent to ASTM C150 Type I and without additives was used in the concrete mixture.The cement content for all mixtures was kept constant and equal to 351 kg/m^3.

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Table 2. Mix proportion (in mass) of materials to produce the concrete mixtures

Mixtures	**RAC-0**	**RAC-30**	**RAC-50**	**RAC-100**
Recycled aggregate rate	0%	30%	50%	100%
Cement	1	1	1	1
Sand	2.42	2.42	2.42	2.42
Natural coarse agreggate	2.58	1.81	1.29	-
Recycled concrete aggregate	-	0.66	1.10	2.19
w/c ratio	0.68	0.68	0.68	0.68
Cement content (kg/m³)	351.7	351.7	351.7	351.7

3.2 Mixing method

During the mixtures it was not used pre-saturation, pre-wetting, mixing water compensation or other methods to reduce the absorbed mixing water by RCA, as well as no superplasticizer was used. Instead, a high workability dosage was adopted. All concrete mixtures were produced using the Two-Stage Mixing Approach (TSMA) proposed by Tam and Tam(2008) in order to improve the compressive strength of the concrete mixtures with RCA and thus decrease their strength variability.The mixing procedure was as shown in Figure 5and consists of dividing the mixing water into two portions and introducing them to concrete mixture in two stages. In the first stage, after all the aggregates have been mixed for 60 s, half of the mixing water is added into the mixture and the mixing continues for an additional 60 s. Thereafter, cement is introduced into the mixture and the mixing process continues for 30 s. Finally, in the second stage, the remaining half of the mixing water is introduced into the mixture and then mixed for more 120 s.

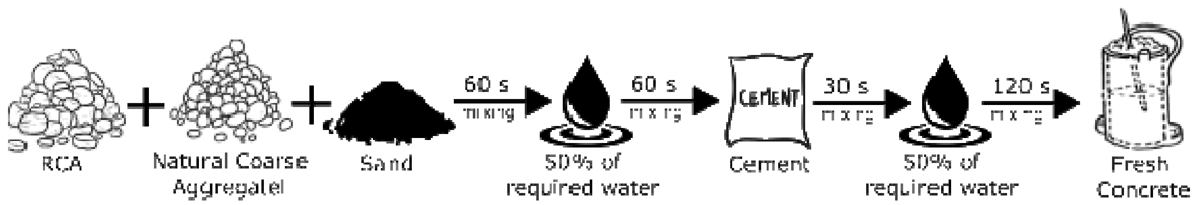

Figure 5. Two-staged mixing method for materials addition

3.3 Concrete tests

After each mixture, the properties of concrete were evaluated in both fresh and hardened states. In the fresh state the workability was evaluated using the slump test according to Brazilian standard code (ABNT NBR NM 67:1998)and the readings were executed after finish the mixtures. For testing concrete in the hardened state, a total of 80 cylindrical (100 x 200 mm) specimens were manufacturedaccording to Brazilian standard code (ABNT NBR5738: 2015).Hand compaction method was used and the samples were kept in their molds and covered with a plastic foil to prevent water loss during the first 24h. After that, the specimens were removed from the molds and stored in saturated calcium hydroxide solution until the test day.The surface regularization method adopted was a mechanical wear method through grinding using a diamond wheel established by ABNT NBR5738: 2015.

In order to determine theproperties of the hardened concrete, series of four tests were carried out on each mixture. The compressive strength (ABNT NBR 5739:2018) has been determined on specimens 7, 14, 28 and 91 days old. In addition to the compressive strength

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analysis, tensile splitting strength (ABNT NBR 7222:2011), modulus of elasticity (ABNT NBR 8522:2017), density, voids ratio and water absorption (ABNT NBR 9778:2005) were performed at 28 days. A universal servo-hydraulic press of 600 kN maximum load was used to determine the mechanical properties.The number of specimens for the experimental tests is shown in Table 3.

Table 3. Number of specimens for each experimental test

Concrete mixtures	**RAC-0**				**RAC-30**				**RAC-50**				**RAC-100**			
Age of concrete	**7**	**14**	**28**	**91**	**7**	**14**	**28**	**91**	**7**	**14**	**28**	**91**	**7**	**14**	**28**	**91**
Compressive strength	3	3	4	1	3	3	4	1	3	3	4	1	3	3	4	1
Modulus of elasticity			3				3				3				3	
Tensile splitting strength			3				3				3				3	
Density, voids ratio and water absorption			3				3				3				3	
Number of specimens for age	**3**	**3**	**13**	**1**	**3**	**3**	**13**	**1**	**3**	**3**	**13**	**1**	**3**	**3**	**13**	**1**
Total of specimens	**20**				**20**				**20**				**20**			

4. Results and Discussion

4.1 Workability, water absorption, voids ratio and density

There is a relationship between the voids ratio, the water absorption and the workability. The last is the most important property of the fresh concrete. Table 4shows the results of slump test of fresh concrete mixtures and shows that the slump of RAC-100 was 10.6% lower than the control concrete (RAC-0). However, even with this reduction in slump, slump ranged from 210 to 235 mm and the workability remained high, showing no difficulty in its employment. Therefore, for the tested mixing composition the negative effects of recycled aggregate water absorption were not significant and there are no significant workability decrease due to the replacement of NCA by RCA.

The samples made with RCA have lower slump than the referenceconcrete. This was expected, since the increment in replacement rate reduce the slump. The decrease workability of concrete containing RCA is due to the higher absorption capacity of RCA, the rougher surfaces and more irregular shapes. As the w/c ratio was kept constant (Table 2), the RCA has higher absorption capacity than the NCA (Table 1 and Table 4) and no additional mixing water was added in the mixtures containing RCA the consequence is the less workability.

Table 4. Slump values, water absorption and voids ratio of coarse aggregates

Mixtures	**Slump (cm)**	**Water absorption of coarse aggregates (%)**	**Water absorption of concrete (%)**	**Voids ratio (%)**	**Density (g/cm³)**
RAC-0	23.5	1.60	6.28	14.37	2.67
RAC-30	22.5 (-4.2%)	2.83 (+76,9%)	6.49 (+ 3.3%)	14.63 (+ 1.8%)	2.64 (-1.1)
RAC-50	21.5 (-8.5%)	3.65 (+128,1%)	6.81 (+ 8.4%)	15.00 (+ 4.4%)	2.59 (-3.0%)
RAC-100	21.0 (-10.6%)	5.70 (+256,2%)	7.27 (+ 15.8%)	15.76 (+ 9.7%)	2.57 (-3.7%)

Table 4 shows the results of water absorption of coarse aggregates. The absorption of coarse aggregates was calculated by weighting the amount of natural and recycled aggregates in each mixture. The natural coarse aggregate (NCA) was taken as reference to calculate the

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percentage of both the slump and the water absorption shown in the Table 4. There is a relationship between the slump and the water absorption of the coarse aggregates (Figure 6). An explanation for the decrease of the workability is the higher water absorption of RCA, in comparison with NCA, that decreases the amount of free water in the mixture.

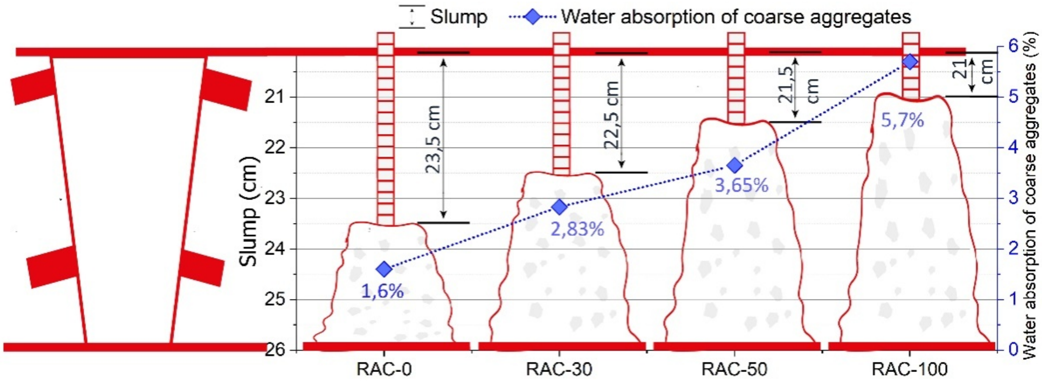

Figure 6. Average water absorption and slump different RCA replacement rates

The determination of density, voids ratio and water absorption of concrete followed the recommendations ABNT NBR 9778:2005.Figure 7clearly shows that thevoid ratio and water absorption capacityof concrete increase asfunction of theRAC content. Both physical properties are related to the amount of ARC, which also has higher water absorption due to the adhered mortar. The use of 100% of recycled coarse aggregates increased absorption by 15.75% and voids index by 9.67%.Results were submitted to variance analysis (ANOVA), different letters (a–c) represent significantly different means ($P \leq 5\%$).

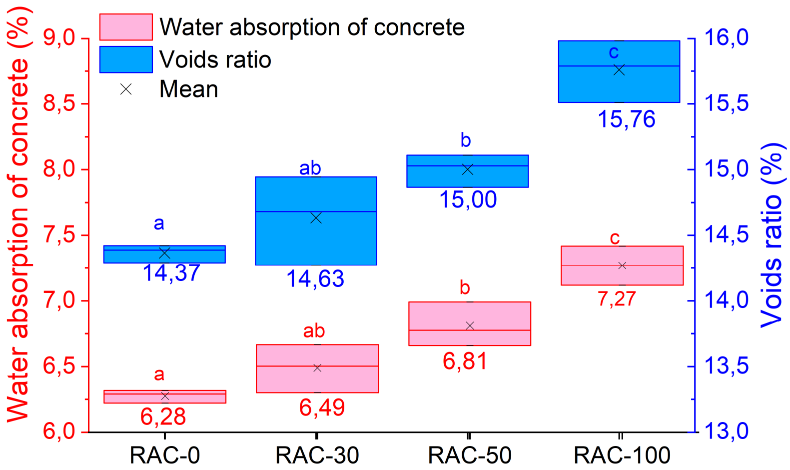

Figure 7. Water absorption and Voids ratio

The substitution of NCA by ARC influences the decrease of density of concrete because ARC has lower specific mass in relation to the natural coarse aggregate. The results obtained in this test are presented inFigure 8. Through the ANOVA, it was observed that densities of the recycled concretes groups (RAC-30, RAC-50 and RAC-100) are statistically equivalent to a significance level of 5% (same letters (a-b) represent non-significant difference means).Replacing 100% of natural coarse aggregates by ARC decreases the density by only 3.74%.Large heterogeneity in terms of density and water absorption capacity was

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expected (KHOURY et al., 2018). The greater variability indensity for RAC-50 may be caused by the variability of RCA (aggregates with almost 100% natural aggregates or grains with large amounts of adhered cement paste).

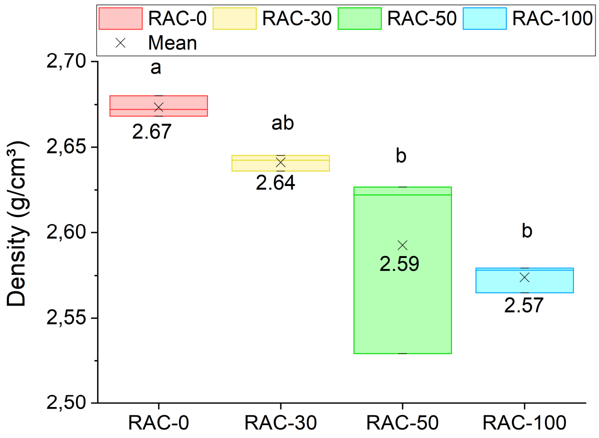

Figure 8. Density results

3.2 Compressive strength

The compressive strength test consisted in applying a constant deformation rate in the upper plate until aggregate displayed rupture (Figure 9).

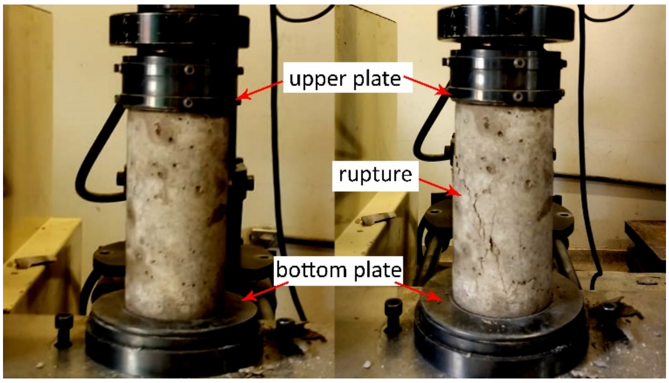

Figure 9. Compressive strength test

Figure 10 shows the average compressive strength test results of the four concrete groups for samples at 7, 14, 28 and 91 days. Despite the use of early hardening cement, there was a considerable increase in strength between 7 and 91 days in all concrete groups, however the largest increase was 35.66% for the reference concrete (RAC-0).

At 7, 14 and 28 days, the reference concrete (RAC-0) presented the lowest compressive strength. These results were already expected due to the no extra water addition to the mixtures with RAC resulting in a higher w/c ratio and consequently increasing the compressive strength of the groups RAC-30, RAC 50 and RAC-100.

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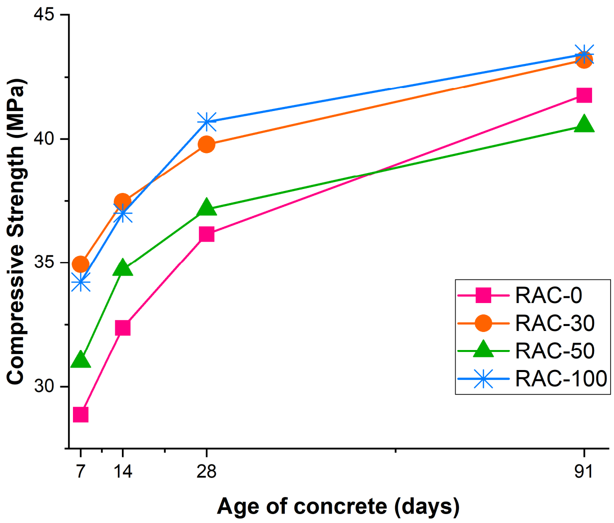
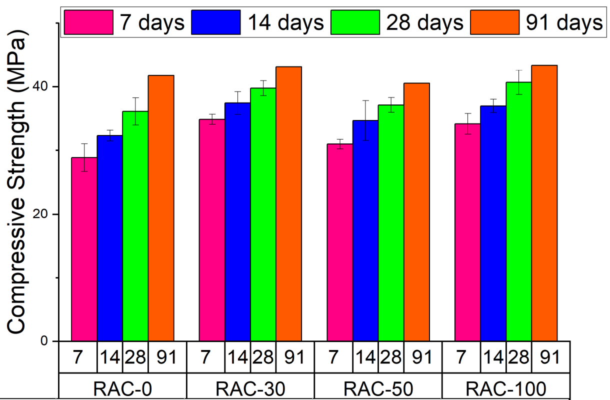


Figure 10. Average compressive strength for different RCA replacement rates

Test mean results and standard deviations of compressive strength are showed in Figure 11. At 7 days, the substitution of 100% of NCA by RCA generated an average compressive strength increase of 18.50% compared to RAC-0. However, the increase in compressive strength is not linear with the increase in substitution content. In addition, this difference in compressive strength between the reference concrete and the recycled concretes decreases as the concrete age increases. At 91 days, the average compressive strength of RAC-30and RAC-100 were, respectively, 3.42%and 3.40% higher than the average compressive strength of the reference concrete. The average compressive strength of RAC-50 were 2.95% lower than the reference concrete at 91 days.



	RAC-0	RAC-30	RAC-50	RAC-100
7 days	28,87	34,93	31	34,21
14 days	32,37	37,46	34,72	37
28 days	36,16	39,78	37,16	40,68
91 days	41,76	43,19	40,53	43,42

Figure 11. Test mean results and standard deviations of compressive strength

3.3 Tensile splitting strength

The tensile splitting strength test followed the procedure specified in ABNT NBR 7222: 2011 where the specimens were positioned horizontally between the parallel horizontal plates and a constant deformation rate wasapplied in the upper plate until the specimen displayed rupture (Figure 12).

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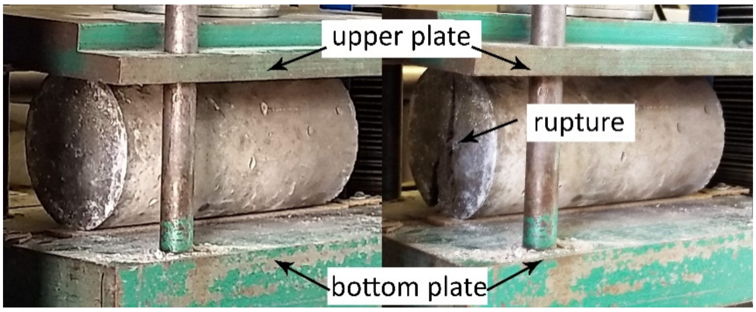
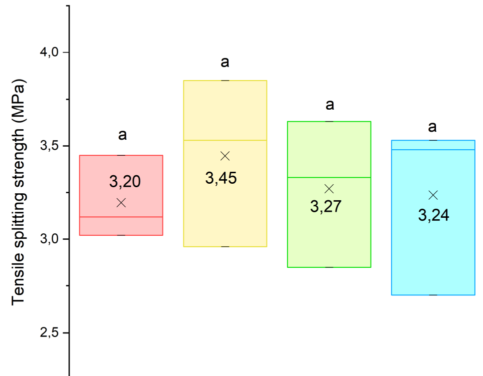


Figure 12. Tensile splitting strength test

The results of this test are shown in Figure 13,same letters (a) represent non-significant difference means. The average tensile splitting strength values of the groups RAC-0, RAC-30, RAC-50 and RAC-100 are statistically equivalent to a significance level of 5% (ANOVA – Analysis of variance). These results demonstrate that the replacement of natural coarse aggregates by recycled ones does not interfere in the tensile splitting strength of concrete.According to the test results, apparently, there is no relationship between the replacement ratio of the NCA by RCA and the tensile splitting strength.



	CARC-0	CARC-30	CARC-50	CARC-100
Mean	3,2	3,45	3,27	3,24
Standard Deviation	0,23	0,45	0,39	0,47

Figure 13. Tensile splitting strengthresults

In the absence of experimental tests, NBR 6118: 2014 proposes anequation toestimate the tensile strengththat associate the tensile strength with the compression strength(Equation 2). The graph in Figure 14shows the experimental and normative tensile strength values, these values are also compared with the compressive strength values used in this equation. The values obtained in the Equation 2were overestimated for all concretes, however the biggest difference was for RAC-100, with a difference of only 9.57%.

$$f_{ct,m} = 0.3 \cdot f_{ck}^{2/3} \qquad (2)$$

$f_{ct,m}$ = mean tensile strength of concrete (MPa);
f_{ck} = compressive strength of concrete at 28 days (MPa);

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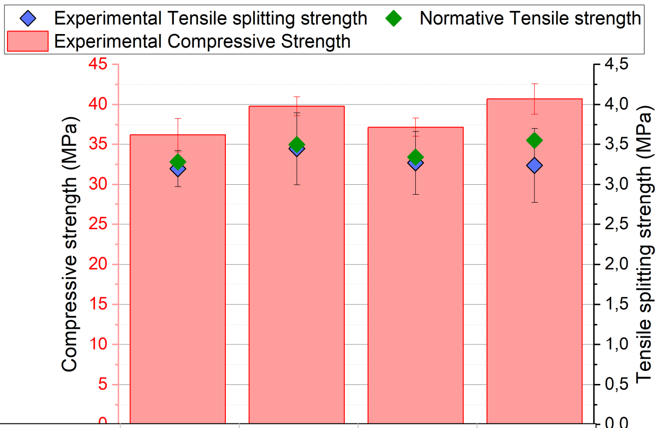
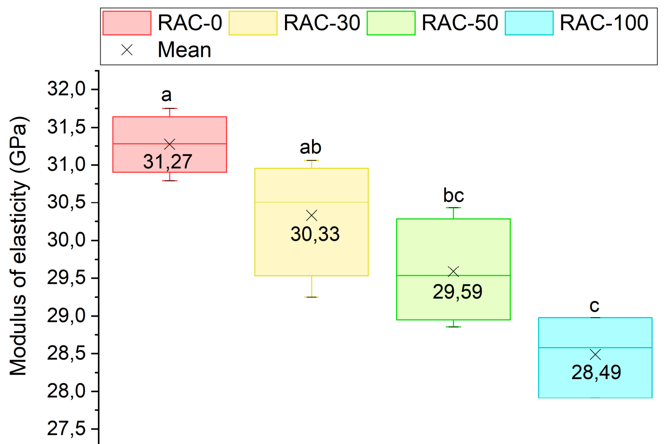


	RAC-0	RAC-30	RAC-50	RAC-100
Experimental Tensile Splitting Strength	3,2	3,45	3,27	3,24
Normative Tensile Strength	3,28 (+2,5%)	3,5 (+1,4%)	3,34 (+2,1%)	3,55 (+9,57%)
Experimental Compressive Strength	36,16	39,78	37,16	40,68

Figure 14. Experimental and normative tensile strength values

3.3 Elastic Modulus

Concrete samples were submitted to the tests of elastic modulus follow the Brazilian standard ABNT NBR 8522:2017and the average results are shown in Figure 15, which show how the average values decreases with increasing recycled aggregates replacement rate. However, according to the analysis of variance (ANOVA), subsequent groups values are statistically equivalent to a significance level of 5%.Different letters (a–c)in Figure 15 represent significantly different means.



--	RAC-0	RAC-30	RAC-50	RAC-100
Mean	31,28	30,33	29,59	28,49
Standard Deviation	0,39	0,77	0,69	0,54

Figure 15. Modulus of elasticityresults

According to ABNT NBR 6118:2014, when no experimental tests is performed, the value of modulus of elasticity of conventional concrete (natural coarse aggregates)can be estimated using Equation 3. This equation estimates the modulus of elasticity from the

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compressive strength and considers that there is a difference in the relationship between the modulus of elasticity with NCA of different geological origins (basalt, quartzite, limestone and sandstone).The Equation 3is ideal for granite and gneiss aggregates (α_E=1.0)and it should be reduced by 10% (α_E=0.9) and 30% (α_E=0.7), respectively, when it was used limestone or sandstone aggregates. For basalt aggregates the value should be increased by 20% (α_E=1.2).

$$E_{ci} = \alpha_E \cdot 5600\sqrt{f_{ck}} \qquad (3)$$

E_{ci} = modulus of elasticity (GPa);
f_{ck} = compressive strength of concrete at 28 days (MPa);

Figure 14 shows the normative and experimental values of modulus of elasticity for RAC-0, RAC-30, RAC-50 and RAC-100. Although the natural coarse aggregate used is basalt, the elastic modulus obtained for the reference concrete was equivalent to a coefficient α_E = 0.93,closer to the estimated value for limestone.This shows that the normative equations for the modulus of elastic modulus may not be representative even for concrete with NCA.

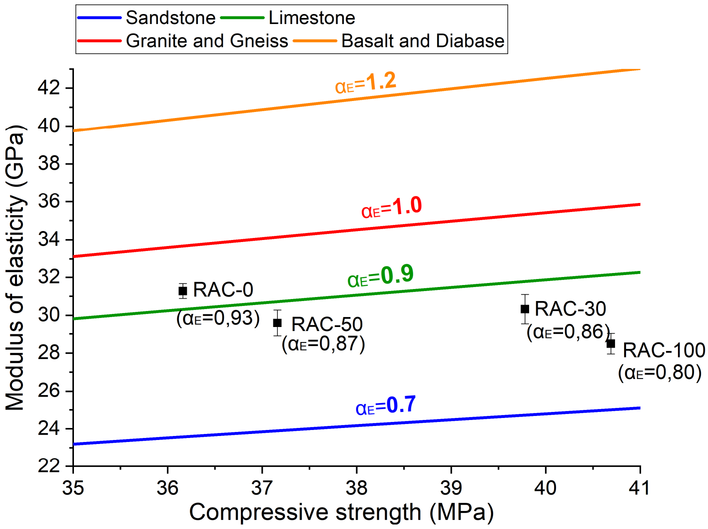

Figure 16. Experimental and normative values of Modulus of elasticity

In Figure 14, it can be observed that higher levels of substitution of natural coarse aggregates for recycled aggregates result in values farther from limestone and closer to those indicated for sandstone. For the replacement of 100% of NCA by RCA, there is a 20% reduction of the value indicated by Equation 3 (α_E=0.80).

4 Conclusions

The experimental results reported in this paper show that recycled aggregates concrete has a potential for application in structures. Although not using any pre-wetting method, the workability remained high, showing no difficulty in its employment.As expected, the greater substitution of natural for recycled concrete aggregates resulted in higher water absorption, voids index and less density.As for the mechanical properties of hardened concrete, the replacement of natural coarse aggregates by recycled concrete aggregates had little influence on compressive strength and tensile strength. However, this substitution had a negative effect on the modulus of elasticity, demonstrating influence on concrete deformability.

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When comparing the experimental values with the theoretical values calculated from NBR 6118: 2014, the elastic modulus values of the recycled concrete presented some discrepancies, similarly to the reference concrete. Regarding tensile strength, the results obtained experimentally had good approximations with theoreticians, both for reference and recycled concrete.

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References

ABRELPE. **Panorama dos resíduos sólidos no Brasil 2018/2019**. São Paulo: [s.n.]. Disponível em: <http://abrelpe.org.br/download-panorama-2018-2019/>.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR NM 67:** concreto: determinação da consistência pelo abatimento do tronco de cone. Rio de Janeiro, 1998.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNTNBR 5738: c**oncreto:procedimento para moldagem e cura de corpos de prova. Rio de Janeiro, 2015

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 5739: c**oncreto: ensaios de compressão de corpos-de-prova cilíndricos. Rio de Janeiro, 2018.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 6118**:projeto de estruturas de concreto:procedimento. Rio de Janeiro, 2014.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 7222: c**oncreto e argamassa:determinação da resistência à tração por compressão diametral de corpos de prova cilíndricos. Rio de Janeiro, 2011.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS.**ABNT NBR 8522:** Concreto:determinação dos módulos estáticos de elasticidade e de deformaçao à compressão. Rio de Janeiro, 2017.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **ABNT NBR 9778:** argamassa e concreto endurecidos: determinação da absorção de água, índice de vazios e massa específica. Rio de Janeiro, 2005.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 15116:** agregados reciclados de resíduos sólidos da construção civil:utilização em pavimentação e preparo de concreto sem função estrutural:requisitos. Rio de Janeiro. 2004.

BARBUDO, A.; DE BRITO, J.; EVANGELISTA, L.; BRAVO, M.; AGRELA, F. Influence of water-reducing admixtures on the mechanical performance of recycled concrete. **Journal of Cleaner Production**, v. 59, p. 93–98, 2013.

BRITISH STANDARDS INSTITUTION. BS 8500-2: "Concrete-complementary British Standard to BS EN 206-1, Part 2: Specification for constituent materials
and concrete". United Kingdom, 2002.

BUTLER, L.; WEST, J. S.; TIGHE, S. L. The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement. **Cement and Concrete Research**, v.41, n.10, p.1037–1049, 2011.

CABRAL, A. E. B. **Modelagem de propriedades mecânicas e de durabilidade de**

Revista Tecnológica - Universidade Estadual de Maringá - ISSN 1517-8048
DOI: 10.4025/revtecnol.v29i1.51289

concretos produzidos com agregados reciclados, considerando-se a variabilidade da composição do RCD. São Carlos, 2007. Tese (Doutorado em ciências da Engenharia ambiental), Universidade de São Paulo, São Carlos.

COMMISSIE VOOR UITVOERING VAN RESEARCH. CUR-VB:“Betonpuingranulaatenalstoeslagsmateriaalvorbeton”, Aanbeveling 4, The Netherlands,1984.

DEUTSCHES INSTITUT FÜR NORMUNG. **DIN 4226-100**:“Aggregates forConcrete and Mortar, Part 100: Recycled Aggregates”. Germany, 2002.

ECKERT, M.; OLIVEIRA, M. Mitigation of the negative effects of recycled aggregate water absorption in concrete technology. **Construction and Building Materials**, v.133, p. 416-424, 2017.

ETXEBERRIA, M.; VÁZQUEZ, E.; MARÍ, A.; BARRA, M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. **Cement and Concrete Research**, v.37, n.5, p.735–742, 2007.

FERREIRA, L.; BRITO, J. DE; BARRA, M. Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. **Magazine of Concrete Research**, v.63, n.8, p.617-627, 2011.

KHOURY, E.; AMBRÓS, W.; CAZACLIU, B.; SAMPAIO, C. H.; REMOND, S. Heterogeneity of recycled concrete aggregates, an intrinsic variability. **Construction and Building Materials,** v.175, p.705-713, 2018.

KUSTER JUNIOR, J. S. **Avaliação da incorporação de agregado reciclado na composição de concretos autoadensáveis**, 2018. 162p. Dissertação (Mestrado em Estruturas de Construção Civil), Universidade Federal de São Carlos, São Carlos.

LEITE, M. B. **Avaliação de propriedades mecânicas de concretos produzidos com agregados reciclados de resíduos de construção e demolição.**2001. 270p. Tese (Doutorado em Engenharia), Universidade Federal do Rio Grande do Sul, Porto Alegre.

LABORATÓRIO NACIONAL DE ENGENHARIA CIVIL. **LNEC E 471**: “Guia para a utilização de agregados reciclados grossos em betões de ligantes hidráulicos”, Lisboa, Portugal, 2006.

MEHTA, P. K.; MONTEIRO, P. J. M. **Concreto. Microestrutura, propriedades e materiais**. 3 ed. São Paulo: IBRACON, 2008.

MORETTI, J. P. **Estudo de viabilidade técnica da utilização da ACBC e do RCC na composição de concretos**. 2014. 158p. Dissertação (Mestrado em Estruturas e ConstruçãoCivil), Universidade Federal de São Carlos. São Carlos.

OBJECTIF TECHNIQUE. **OT70085**: “Instruction technique. Utilisation de matériaux de construction minérauxsecondaires dans la construction d’abris”, Suiça, 2006.

PEREIRA, M. F. (2017). **Comportamento estrutural de pilares mistos parcialmente revestidos submetidos a flexo-compressão**. Tese (Doutorado em Engenharia Civil), Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2017.

TAM, V. W. Y.; TAM, C. M. Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAsand TSMAsc. **Construction and Building Materials**, v.22, n.10, p.2068-2077, 2008.

VERIAN, K. P.; ASHRAF, W.; CAO, Y. Properties of recycled concrete aggregate and their influence in new concrete production. **Resources, Conservation and Recycling**, v.133, n. October 2017, p.30-49, 2018.

WORKS BUREAU TECHNICAL CIRCULAR. **WBTC No.12**: “Specifications facilitating the use of recycled aggregates”, Hong-Kong, 2002.