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Shrinkage and porosity in concretes produced with recycled concrete aggregate and rice husk ash

Retração e porosidade em concretos produzidos com agregados reciclados de concreto e cinza de casca de arroz





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Abstract

The admixture of recycled concrete aggregates (RCA) in new concretes is an interesting alternative in the efforts to mitigate environmental impacts. RCA may increase porosity and change properties of concretes. Rice husk ash (RHA) is employed as supplementary cementitious material may improve concrete properties. The present study investigated the shrinkage of concrete prepared with RCA and RHA, proposing a mathematical model to explain the phenomenon. Concretes were produced with 25% and 50% of coarse recycled aggregate as replacement of natural aggregate, 0%, 10%, and 20% of RHA as replacement of cement, and a water-to-binder ratio of 0.64. Water absorption and capillary and total porosities were analyzed on day 28. Shrinkage tests were conducted on days 1, 4, 7, 14, 28, 63, 91, and 112. The results point to a significant interaction between RHA and RCA.

Keywords: recycled concrete aggregate, rice husk ash, shrinkage, porosity.

Resumo

O emprego de agregado reciclado de concreto (ARC) para a produção de novos concretos é uma alternativa interessante para mitigar impactos ambientais. O ARC pode aumentar a porosidade e impactar negativamente as propriedades do concreto. A cinza de casca de arroz (CCA), empregada como material cimentício suplementar, pode mitigar estes efeitos. Este estudo investiga a retração em concretos produzidos com ARC e CCA, propondo um modelo matemático para explicar os comportamentos observados. Foram elaborados concretos com 25 e 50% de ARC graúdo, e 10 e 20% de CCA em substituição ao cimento, com uma única relação água-aglomerante (0,64). A absorção e água capilar e total, bem como a porosidade, foram avaliadas aos 28 dias. A retração foi medida em 1, 4, 7, 14, 28, 63, 91 e 112 dias. Os resultados indicam um efeito significativo da interação entre ARC e CCA.

Palavras-chave: agregado reciclado de concreto, cinza de casca de arroz, retração, porosidade.

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1. Introduction

The construction industry uses a wide array of cementitious and ceramic products that may be feasibly reused or recycled. By indirectly protecting the environment and promoting the development of new raw materials, construction waste recycling is an environmentally interesting, economically attractive alternative when compared with the use of non-renewable natural resources [1].
Besides affordable prices, excellent resistance to compression and strain explains why the concrete made with Portland cement is perhaps the most widely used construction material. In addition to buildings in general, it is employed in heavy constructions such as roads, dams, and bridges, and estimates place global annual consumption of concrete made with Portland concrete at staggering 33 billion metric tons [2]. However, the clear benefits brought about by such remarkable structural characteristics are offset by the growing environmental concerns surrounding cement production, in that the extraction of non-renewable raw materials and conversion thereof in cement are intrinsically associated with considerable greenhouse gas emissions. Such environmental impacts are partly due to the methods employed to make Portland cement, which are based on heating a mixture of limestone, clay, and other similar materials. The partial sintering of these ingredients produces clinker lumps that are ground and subsequently have a small percentage of calcium sulfate added.
But other ingredients of concrete also raise environmental concerns, like aggregates. Most materials used as aggregates are extracted from natural sites and then subjected to some degree of processing, like crushing and sifting, for instance. However, the use of alternative aggregates such as those from the construction and demolition waste (CDW) has been recently proposed in the effort to address these environmental problems.
The main difficulties in using CDW as aggregate in concrete products are associated with crushing, screening, and dust emissions control, in addition to the segregation of undesired constituents. Despite that, CDW may become a viable option in light of the scarcity of quality natural aggregates and the high costs associated with final waste disposal. Previous research shows that recycled concrete aggregate (RCA) obtained from crushing structural concrete waste does not affect quality of concretes, as long as prior recycling is carried out appropriately [2].
However, it is known that the introduction of porous aggregates in Portland cement concrete will increase the amount of water needed to maintain slump. As a result, the mixture will demand more binder in order to preserve the water-to-binder ratio. In this scenario, rice husk ash (RHA) may be employed as supplementary cementitious materials (SCM), reducing cement consumption and improving properties of the new concrete. Considered waste by the rice industry and therefore easily obtained in rice producing regions, RHA has high amorphous silica content and considerable specific surface, which characterizes it as a super pozzolan. Previous studies have discussed the advantages of adding RHA as pozzolanic material to concrete mixtures, among which improved resistance and durability of the final product, besides the significant environmental benefits associated with the possibility to eliminate waste and reduce carbon dioxide emissions [3,4,5].
This leads to the conclusion that mitigating the environmental impacts associated with concrete includes using mineral admixtures and replacing natural aggregates, indirectly reducing the extraction of non-renewable raw materials. Such efforts in the development of eco-efficient concretes entail using materials so far considered byproducts in another industry that otherwise might end up being disposed of improperly. The well-engineered, controlled application of such replacement materials affords to obtain new final products whose characteristics should be similar to those of conventional concrete.
So, with a view to improving the current knowledge about the use of alternative materials in concrete mixtures and preventing any pathology in concretes made with RCA and RHA, the present study analyzed concrete prepared with these materials based on concrete properties such as water absorption, capillary porosity, total porosity, and shrinkage.

2. Materials and experimental program

2.1 Experimental design

The experimental procedure adopted in this study was based on an n^k factorial design, with n being the levels and k the number of factors considered. Study levels, control factors, and response variables are presented below.
In this design, just one water-to-binder ratio (w:b) was used, 0.64, since large water volumes make more porous concretes, which are also more prone to significant shrinkage. Table 1 shows the levels chosen and respective values of RCA and RHA.
Here, k = 2 and n = 3, which means a factorial design of 32 experiments with 9 concrete mixtures. Three prism and three cylindrical samples were prepared for each combination of control factors.
The response variables analyzed on day 28 were absorption rate, capillary porosity, total porosity. Shrinkage was measured on days 1, 4, 7, 14, 28, 63, 91, and 112 and compressive strength on days 7, 28, 63, 91 and 112.

2.2 Materials

2.2.1 Cement

The cement used (type CP-II-F-32) is composed of limestone filler, an inert mineral admixture [6]. This cement type is usually employed in concrete plants and it was choiced because it does not

Table 1
Factorial design used in this study. Factors and control levels (shrinkage, absorption rate, capillary porosity, total porosity)

Control factors	Study levels		
RHA content (%)	0	10	20
RCA content (%)	0	25	50

Table 2
Chemical, physical, and mechanical characterization of the cement used

Parameter	April 2012 batch	May 2012 batch
Al_2O_3 (%)	4.12	4.12
SiO_2 (%)	19.42	19.39
Fe_2O_3 (%)	2.60	2.59
CaO (%)	60.76	60.78
MgO (%)	4.85	4.93
SO_3 (%)	3.03	3.08
Loss on ignition (%)	6.04	6.08
Free CaO (%)	2.89	2.24
Insoluble fraction (%)	2	2
Alkaline equivalent (%)	0.63	0.62
Hot expansion (mm)	0.50	1.00
Initial setting time (h:min)	03:20	3:30
Final setting time (h:min)	04:30	4:30
Normal amount of water (%)	26.20	26.30
Blaine (cm^2/g)	3.850	3.720
#200 (%)	3.4	4.2
#325 (%)	16.3	15.5
Comp. strength day 1 (MPa)	16.3	16.9
Comp. strength day 3 (MPa)	29.0	29.3
Comp. strength day 7 (MPa)	36.9	36.6
Comp. strength day 28 (MPa)	41.9	41.9
Specific weight (g/cm^3)	3.11	3.11

have pozzolanic materials. Table 2 shows the physical, chemical, and mechanical characterization of the cement used. Due to issues around availability of material, cement of two different batches were used. However, the characterization of the cements of the two batches showed that they did not differ significantly.

2.2.2 Rice husk ash (RHA)

The RHA used is a pozzolan obtained from the combustion of biomass in a fluidized bed reactor to generate energy. The energy company is located in the city of Alegrete, state of Rio Grande do Sul, Brazil, and sells RHA to construction companies under the name of ‘rice husk silica’.

Table 3
Chemical characterization of the rice husk ash used

Parameter	Content (%)
SiO_2	94.99
K_2O	1.01
SO_3	0.57
Cl	0.43
CaO	0.33
MnO	0.20
Al_2O_3	0.18
P_2O_5	0.10
Fe_2O_3	0.06
TiO_2	0.01
MgO	0.01
ZnO	0.00
P.F.	2.12

The chemical characterization of the pozzolan was carried out in the Laboratory of Characterization and Recovery of Materials (LCVM), UNISINOS, using energy-dispersive X-ray fluorescence (ED-XRF) (EDX-720, Shimadzu) and a secondary standard. The results of the ED-XRD analysis are shown in Table 3.

2.2.3 Natural fine aggregate

The natural fine aggregate used was a quartz sand from the Jacuí River, RS, and was characterized in the Laboratory of Construction Materials (LMC), UNISINOS. Grain size distribution, specific weight, and unit weight were evaluated following the procedures described in official Brazilian standards [6-8]. The data obtained are shown in Tables 4 and 5.

2.2.4 Natural coarse aggregate

The natural coarse aggregate (NCA) used was a triturated basaltic rock mined in Linha São Jorge, municipality of Garibaldi, RS.

Table 4
Unit weight and specific weight of the natural fine aggregate used

Test/standard	Value (g/cm^3)
Unit weight/ NBR NM 45 – 2006	1.52
Specific weight/ NBR NM 52 – 2009	2.55

Table 5
Grain size distribution of the natural fine aggregate used

Mesh	Retained fraction (%)	Accumulated retained fraction (%)
6.3mm	1	1
4.8mm	2	3
2.4mm	5	8
1.2mm	6	14
0.6mm	11	25
0.3mm	38	63
0.15mm	35	98
<0.15mm	2	100
Maximum characteristic size (mm)	4.8 mm	
Fineness modulus	2.12	

Table 6
Unit and specific weight of the natural coarse aggregate used

Test/standard	Value (g/cm³)
Unit weight/ NM 45 – 2006	1.40
Specific weight/ NM 53 – 2009	2.67

The aggregate was characterized in LMC, UNISINOS. Analyses included grain size distribution, specific weight, and unit weight, according to the official Brazilian standards [6-8]. The characterization data of the coarse aggregate are shown in Tables 6 and 7.

2.2.5 Recycled concrete aggregate

The RCA used was the waste generated in the production of alveolar slabs with conventional setting. Compressive strength (fck) of the material was 35 MPa. The concrete waste was triturated in a jaw crusher with a 20-mm pass gradation. After crushing, RCA was sieved and the fraction between 19 and 4.8 mm was used. Grain size distribution of RCA is shown in Table 8. The maximum size of the RCA aggregate was below NCA.

Even though using just the fraction remaining between the sieves 19 and 4.8 mm, the RCA grain size distribution was altered in relation to NCA, and as well it presented a maximum size grain of 25 mm that is greater than NCA. It is understood that in order to isolate the size grain distribution it is recommended put both aggregate type in same size distribution curve. This adjust was not done, due to the aim of this work was to employ the RCA in the closer conditions of it is processed.

In order to establish the amount of water to be used in order to compensate the higher RCA water absorption in the concrete mixtures prepared with RCA, the amount of water absorbed by RCA was evaluated according to a two-stage procedure described in a previous study [10].

The water absorption curve of RCA is shown in Figure 1. Water absorption was 6.29% after 10 min and 10.34% after 24 h. Data regression indicated that absorption after 10 min is approximately 6%, and the value was adopted as water compensation rate. Saturation state was observed after 31.6 min, indicating absorption of

Table 7
Grain size characterization of the natural coarse aggregate used

Mesh	% retained fraction	% retained fraction (accumulated)
25 mm	0	0
19 mm	0	0
12.5 mm	39	39
9.5 mm	39	78
6.3 mm	22	100
<6.3 mm	0	100
Maximum diameter (mm)	19	
Fineness modulus	6.78	

Table 8
Grain size distribution of the recycled concrete aggregate used

Mesh	% retained fraction	% retained fraction (accumulated)
25	0	0
19	36	36
12.5	43	79
9.5	10	89
6.3	10	99
<6.3	1	100.0
Maximum diameter (mm)	25	
Fineness modulus	7.25	

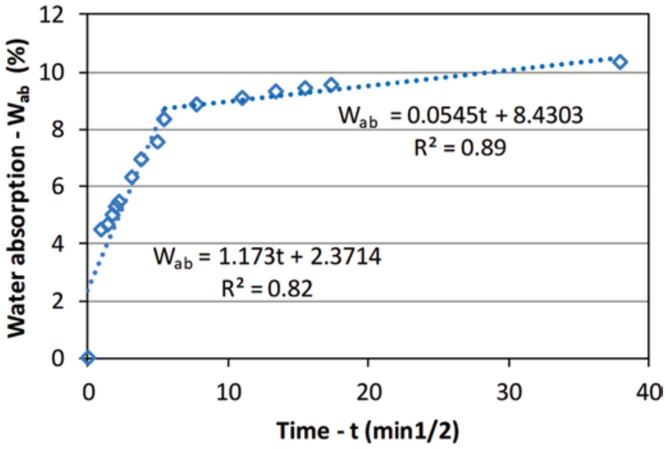

Figure 1
Water absorption curve of the recycled concrete aggregate

8.96%. The unit weight of RCA is 1.13 g/cm³, and specific weight is 2.21 g/cm³.
Previous studies [11,12] indicated that the amount of water to compensate the higher water absorption of RCA is calculated using 50% of the RCA water absorption at 10 min.
Water absorption at 10 min was 6%, obtained from the adjusted curve for the RCA water absorption characterization. The amount of compensation water in each one of the batches with RCA was determined using de Equation 1.

$$M_{H_2O} = 0.50 \times ABS_{10min} \times M_{RCA} \quad (1)$$

Where,
M_{H2O} = amount of water used as compensation
ABS_{10mim} = absorption at 10 min
M_{RCA} = amount of RCA

2.2.7 Additive

A polycarboxylate-based additive was used as water-reducing additive with high-range (superplasticizer admixture). The maximum amount used in some concrete mixtures was 0.28%, according to the range recommended by the manufacturer (0.2% to 1%). Table 9 shows the characteristics of the additive used.

2.3 Production of concrete

Mixtures were prepared based on a mortar content of 55% and consistency of 100 ± 20 mm measured using the slump test using the only level of the water-to-binder ratio that remained constant in the mixtures with the RHA and RCA admixtures. The consistency of each mixture was adjusted using the superplasticizer admixture. These conditions were previously tested in a pilot study.
The replacement of cement by RHA and of natural aggregate by RCA was done on a volume basis. The amount of each material used in each mixture was measured in mass. The mass of RHA and RCA was calculated using volume-compensated weight, because of the significant difference in specific weight of these materials. This affords to maintain constant the volume of binder and the ratio of mortar volume to coarse aggregate volume.
The order of materials was chosen based on previous studies [11-13], and it is listed below:
1. Natural coarse aggregate and RCA, according to the mixture;
2. 50% water;
3. Cement and RHA, when required;
4. Natural fine aggregate;
5. 50% water.

The mixtures containing RCA were prepared mixing it to the natural aggregate and the amount of water required to compensate the higher water absorption of RCA. Next, the mixer was stopped and covered for 10 min so as to prevent the evaporation of water, before proceeding to the other stages listed above.
Consistency was evaluated using the slump test 8 min after the incorporation of cement to the mixture. Additive was included when necessary, mixing proceeded for another 2 min, and the slump test was repeated [14].

2.4 Capillary water absorption test method

The capillary water absorption for concretes was conducted according to the procedure defined in RILEM TC 116 PCD [15] with modifications [16] for samples with a water-to-binder ratio of 0.64 on day 28.
This test generates the water absorption profile of the material over time. Based on this profile it is possible to calculate the capillary water absorption rate (water sorptivity), total water absorption.
The data obtained were used to calculate the absorption rate and total and capillary porosities. Suction and saturation curves were plotted for all concrete mixtures.
Absorption rate was calculated dividing the capillary suction curve slope by the volume of the sample [17]. Total porosity was calculated based on the differences in mass and volume of the sample. Capillary porosity was obtained dividing sample weight after 72 h by its volume.

2.5 Evaluation of shrinkage due to setting

The shrinkage assay was carried out according to the standards ASTM C157:2011 and ASTM C490:2012
Three samples were cast for each concrete mixture. Samples were covered with a glass lid to prevent evaporation and protect the material in a controlled environment (21 ± 2ºC and 60 ± 10% relative humidity).
Twenty-four hours later, blocks were demolded and were left to set

Table 9
Characteristics of the admixture used

Characteristic	Value
Density	1.07(g/cm³)
Percent amount used (considering cement amount)	0.2 to 5.0 (%)
Chlorides	< 0.1 (%)
Alkalis	< 1.0 (%)

Source: Product datasheet (MC-Bauchemie, 2013)

Figure 2
Equipament to measure length variation

for another 7 days in wet curing. After this period, samples were placed again in the controlled environment room (21 ± 2ºC and 60 ± 10% relative humidity).
Length was measured on days 1, 4, 7, 14, 28, 63, 91, and 112 into the setting process as described below. Figure 2 illustrates the equipment used to read shrinkage values.
It should be stressed that the setting, demolding, wet curing, and final setting were carried out in the controlled environment room. The tests were conducted using a calibrated device to measure dimensional variation concrete in the same room. Three readings were made for each of the three specimens of a concrete mixture. Samples were always placed on the same position for all tests. The equipment was calibrated for each sample using a specific standard bar.

2.6 Compressive strength

The compressive strength was carried out according ABNT NBR 5738:2003 e ABNT NBR 5739:2003. Three samples were cast for each concrete mixture and age of test. The tests were done on days 28, 63 and 112.

2.7 Statistical analysis

The data obtained were analyzed by non-linear multiple regression and analysis of variance (ANOVA).

3. Results and discussions

3.1 Water absorption rate

The data of water absorption over time were treated and the capillary water absorption rate was calculated. The water absorption rate for mixtures on day 28 are shown in Table 10 and Figure 3.
In general, concretes mixtures without RHA had the higher water absorption rates. Moreover, the use of 25% RCA reduces absorption rate by 3,2%, while 50% RCA decreases the values of the parameter by 13%, when compared to the concretes made only with regular coarse aggregate. This effect can be attributed to any reduction in the paste's porosity due to the absorption of the mixing water by RCA, even though an additional quantity of water was used in the mixture for compensate the absorption of water by the RCA. As well, in general the RHA reduces the rate of capillary water absorption, in order of 30% using a content of 10% and 50% using a content of 20%.
Moreover, in this work when both RCA and RHA were employed together, the rate of capillary water absorption quite decrease, in averange of 55% if it is compared the mixtures with both content of RCA and 20% RHA with the plain concrete. This effect can be attributed a synergic effect between pozzolanic reaction of RHA and reducing effective w/b ratio due to water absorption from the mixture by the RCA. These combined effects lead to an modification in the pore structure, with reduction of size and enhance of tortuosity [24].

3.2 Capillary porosity

Capillary porosity (Table 11) represented between 70% and 90%

Table 10
Absorption rate

RCA (%)	Absorption rate (mm/h$^{1/2}$)		
	RHA (%)		
	0	10	20
0	1.32	0.86	0.61
	1.26	0.87	0.66
	1.13	0.76	0.61
25	1.10	0.49	0.65
	1.18	1.00	0.53
	1.31	0.88	0.51
50	1.28	0.87	0.53
	1.03	0.80	0.53
	0.95	0.82	0.57

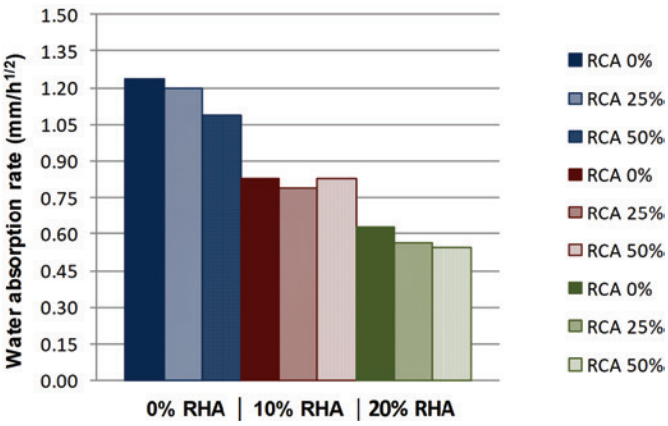

Figure 3
Absorption rate on day 28

Table 11
Capillary porosity

RCA (%)	Capillary porosity (%)		
	RHA (%)		
	0	10	20
0	13.1	0.86	0.61
	12.8	11.8	0.66
25	12.8	5.7	0.61
	12.9	10.9	0.66
50	12.4	6.8	4.5
	11.4	6.9	4.5

Table 12
Total porosity

RCA (%)	Total porosity (%)		
	RHA (%)		
	0	10	20
0	13.6	12.2	7.8
	13.1	11.4	7.4
25	13.5	13.1	6.3
	13.6	11.3	6.2
50	13.2	10.3	6.4
	12.5	10.1	6.3

of total porosity, depending on the amount of RHA and RCA and on the water-to-binder ratio.

Figure 4 illustrates the averages for concretes capillary porosity after on day 28. In this study, capillary porosity in general tended to diminish with the admixture of RCA and RHA, despite the high porosity of RCA concrete. The concrete mixtures prepared with 0% RHA and 0% and 25% RCA remained essentially stable, though those made with 50% RCA presented an 8% decrease in capillarity, compared with the mixture with 0% RCA and RHA.

The mixtures prepared with 10% RCA had lower capillary porosity, compared with those made with 0% RCA. Also, when the 0% RHA and 0% RCA mixture is compared with the 10% RCA and 0% RHA mixture, the drop is of approximately 12%. The adding RCA reduced porosity, namely by 12% and 40% in mixtures with 25% and 50% RCA, respectively. This behavior can be attributed to the grain size of RCA and its porosity. The grain size distribution of RCA, with a larger maximum grain size than NCA, led an improvement in particle packing of the concretes. Further, as greater is the maximum size of recycled aggregate greater is the probability to increase the water absorption of the mixture by the RCA, even using an additional water, as related. The increase of water absorption by the RCA can reduce the water/binder from the cement paste that effectively will promote the development of pore structure, leading to reduce the porosity. [2]. The mixtures made using 20% RHA exhibited even lower capillary porosity values. Compared with the 0% RCA and RHA mixture, capillary porosity of the 20% RHA and 0% RCA was almost 57% lower. Adding RCA intensified this decrease, of approximately 21% when comparing the 20% RHA and 0% RCA mixture with the 20% RCA and 25% or 50% RCA.

The decrease in the capillary porosity may probably be a result of the absorption of water of mixing due to RCA porosity.

3.3 Total porosity

The results of total porosity (Table 12) were analyzed according to the same inclusion criteria used for absorption rate and capillary porosity.

Total porosity followed the trend exhibited by porosity values, for all combinations. The results of the ANOVA analysis of isolated effects of each of the variables studied and respective interactions are shown in Table 13.

The p-value of the ANOVA of total porosity data was less than 0.05 for the control factors CCA and RCA, which indicates that these factors have a significant effect on the properties studied, in a confidence

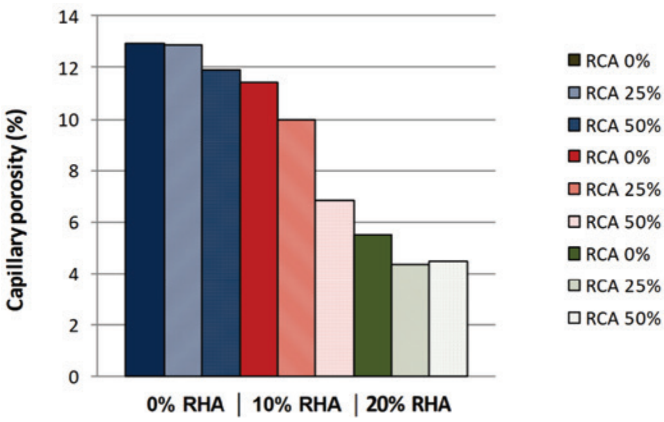

Figure 4
Capillary porosity on day 28

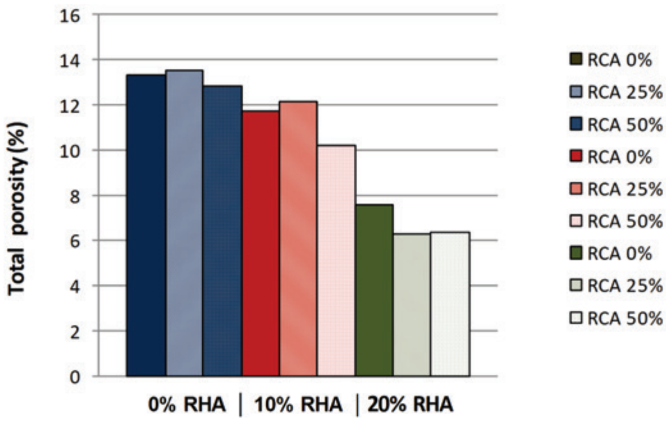

Figure 5
Total porosity on day 28

Table 13
ANOVA – total porosity

Source	df	SS	SM	F test	Significance – p
RHA	2	135.11096	67.555479	253.32696	0.000000
RCA	2	3.8944163	1.9472082	7.301855	0.013052
RHA*RCA	4	2.9600472	0.7400118	2.7749775	0.093741
Error	9	2.4000577	0.2666731	–	–

df = degrees of freedom; SS = square sum; SM = square mean; RHA = rice husk ash; RCA = recycled cement aggregate.

level of 95%. On the other hand, the interaction between RCA and RHA does not have any significant effect, since the p-value was 0.093741. Figure 5 shows the mean values for total porosity.
The effect of using RHA alone reduced total porosity of the concrete mixtures, depending on the amount used. The higher the RHA level, the lower the total porosity. For the 10% RHA concrete, the drop in total porosity was of approximately 14%. When 20% RHA was used, this decrease reached 49%, compared with the mixtures using 0% RHA.
Similarly to Bezerra et al. [19], the concretes with the lowest porosity values were those prepared with high percentages of RHA. Also, concretes prepared with pozzolans had reduced porosity values with time [20].

3.4 Shrinkage

The data of shrinkage caused by drying were analyzed using non-linear multiple regression, testing all factors and levels. The mean values of three readings for each sample are shown in Table 14.
When examining Table 14, it should be remembered that the results obtained until day 7 are not associated with shrinkage due to drying, since the samples were immersed during this time. A concrete that is transferred from a dry environment to container with water experiences the opposite of shrinkage, that is, expansion. This effect is overcome by shrinkage during drying [21].
The model proposed to determine shrinkage in concretes prepared with RCA in place of fine natural aggregate and RHA for Portland cement is represented by a non-linear multiple regression equation (Equation 2).

$$S = b_0 + b_1 RHA + b_2 RCA + b_3 AGE + b_{12}\left[\frac{(RCA+1)}{(RHA+1000)}\right] + b_{13}\left[\frac{(AGE+1)}{(RCA+0.1)}\right] + b_{23} RCA \cdot RHA \quad (2)$$

Table 14
Shrinkage values for concrete mixtures of all ages

Mixtures		w:b ratio	Mean						
RHA (%)	RCA (%)		Day 4 (µm)	Day 7 (µm)	Day 14 (µm)	Day 28 (µm)	Day 63 (µm)	Day 91 (µm)	Day 112 (µm)
		–	-35.33	-51.67	-25.00	-16.00	14.00	31.00	21.33
0	0	0.64	-23.33	-60.33	-23.67	-12.67	20.33	24.33	38.33
		–	-68.00	-25.00	-12.33	20.67	50.00	56.33	80.67
		–	-12.00	-51.67	-10.67	31.00	58.67	66.67	81.67
10	0	0.64	-31.00	-53.33	-14.00	20.00	50.33	63.33	51.00
		–	-10.00	-45.00	44.00	42.67	74.33	93.67	86.00
		–	-10.00	-21.00	21.00	63.67	74.00	89.67	122.33
20	0	0.64	-5.67	-11.67	26.33	63.00	108.67	101.33	122.33
		–	45.00	38.33	23.67	98.00	113.00	124.33	136.33
		–	-54.00	47.33	-65.67	-32.67	-13.67	14.00	28.33
0	25	0.64	-69.33	-64.33	-24.00	-3.00	23.00	33.00	42.00
		–	-61.67	-48.67	5.33	15.67	37.33	56.00	67.67
		–	-54.00	47.33	-65.67	-32.67	-13.67	14.00	28.33
0	25	0.64	-69.33	-64.33	-24.00	-3.00	23.00	33.00	42.00
		–	-61.67	-48.67	5.33	15.67	37.33	56.00	67.67
		–	-25.33	-16.67	-1.67	13.33	30.17	59.33	47.67
0	50	0.64	-18.67	-12.33	-13.33	1.00	28.67	57.33	61.33
		–	-8.67	-12.00	-8.00	31.00	57.33	61.67	93.00
		–	48.67	-2.67	47.00	79.67	104.67	117.00	119.67
10	25	0.64	-0.67	-3.00	22.67	34.67	95.00	73.67	83.33
		–	-15.00	-38.67	-22.33	33.33	88.00	74.33	64.33
		–	31.33	-50.00	38.00	65.33	105.00	114.67	120.00
10	50	0.64	40.00	2.33	39.33	74.00	113.67	125.00	131.00
		–	-33.67	-79.00	-32.00	69.67	109.33	119.83	125.50
		–	-15.33	-22.67	25.67	27.33	68.67	105.33	78.67
20	25	0.64	-6.33	-13.67	23.00	45.00	73.33	85.67	76.67
		–	-12.67	-28.00	0.67	15.67	74.67	80.67	59.33
		–	-47.67	-19.00	3.00	11.67	47.33	73.33	44.00
20	50	0.64	-32.67	-57.33	-15.33	4.00	54.33	63.00	63.00
		–	-2.00	-26.33	48.00	44.33	67.00	101.00	112.33

Table 15
ANOVA of the shrinkage results obtained

Source	Df	SS	SM	F test	Significance – p
Model	7	5.50E-01	7.86E-02	1.15E+02	0
Residual	182	1.24E-01	0.0006824	–	–
Total	189	6.74E-01	–	–	–
Adjusted total	188	5.01E-01	–	–	–

df = degrees of freedom; SS = square sum; SM = square mean.

Table 16
Significant parameters for the factors analyzed considering shrinkage

Factor	Parameter	Estimate	Standard error	T Test	p
Constant	bo	7.1793	1.36472	5.2606469	0.000000
RHA	b1	-0.0043	0.00132094	3.2596711	0.000000
RCA	b2	7.2241	1.36559	5.2900871	0.000000
AGE	b3	0.00103	5.72213E-05	18.038388	0.000000
RHA*RCA	b12	-7223.6	1365.63	5.2896026	0.000000
CCA*AGE	b13	-0.00002	9.52372E-06	1.9893382	0.023572
RCA*AGE	b23	-0.0071	0.0013389	5.3323923	0.000000

RHA = rice husk ash; RCA= recycled concrete aggregate; AGE: age in days.

Where:
S = shrinkage (μm)
RHA = amount of RHA used (0%, 10%, 20%)
RHA = amount of RCA used (0%, 25%, 50%)
AGE = age of samples (4, 7, 14, 28, 63, 91, 112 days)
Tables 15 and 16 show the regression results.
The statistical model resulted in an ANOVA with a correlation coefficient (r^2) of 0.752, indicating that it is the best-fit model for 75.2% of the values obtained in the shrinkage test. A p-value below 0.05 shows that the variables represented in the model correlate with a confidence level of 95%.
The model used to explain shrinkage is presented in Equation 3.

$$S = 7.18 - 0.0043RHA + 7.22RCA + 0.001AGE - 7223{,}6\left[\frac{(RCA+1)}{(RHA+1000)}\right] - 0.00002\left[\frac{(AGE+1)}{(RCA+0.1)}\right] - 0.0071RCA \cdot RHA \quad (3)$$

Where:
RHA = amount of RHA used (0%, 10%, 20%)
RHA = amount of RCA used (0%, 25%, 50%)
AGE = age of samples (4, 7, 14, 28, 63, 91, 112 days)
Considering the wide variability of RCA and RHA, the interactions between them (which are not completely understood), and the correlation coefficients reported in previous studies about shrinkage, recycled aggregates, and sensitivity of this assay, the model proposed was validated.
The effect of RHA content on the shrinkage along time are presented in Figures 6, 7, and 8.
Figure 6 shows the values obtained for concretes prepared without RCA.

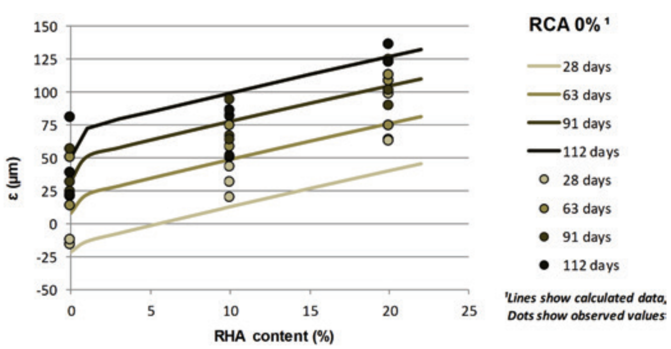

Figure 6
Shrinkage test, replacement with RHA with 0% RCA for mixtures of different ages

The mixtures prepared with RHA and without RCA presented similar shrinkage, independently of age. When mixtures of all ages are compared, shrinkage of the 10% RHA mixture is approximately 40 μm larger than that of the control mixture. For the 20% RHA mixture, shrinkage is roughly 70 μm larger than that of the control mixture.
In other words, shrinkage increases with the levels of RHA in mixtures. This may be associated with the smaller internal pore structure due to the presence of the mineral admixture, as described in previous studies [22, 23]. Mineral admixtures tend to reduce pore diameter at the same time that pore numbers

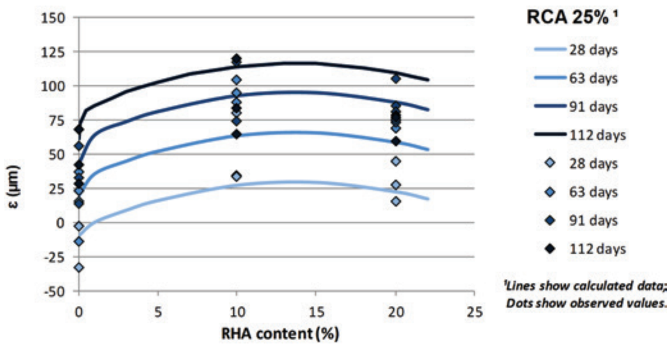

Figure 7
Shrinkage test, replacement with RHA with 25% RCA for mixtures of different ages

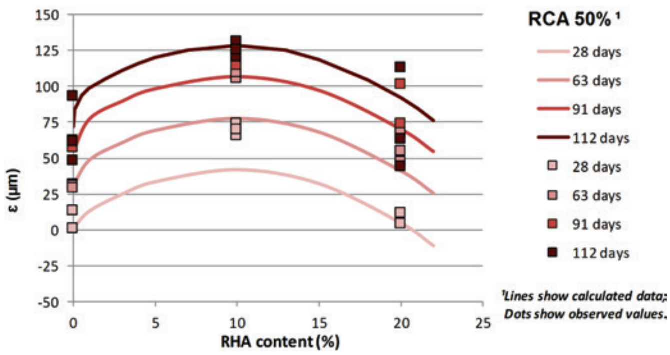

Figure 8
Shrinkage test, replacement with RHA with 50% RCA for mixtures of different ages

increase. The presence of small pores increases shrinkage values. Figure 6 shows the parallel curves that simulate shrinkage with time in mixtures containing 0% RCA and different RHA levels.
Figure 7 illustrates the effects of RHA when added to a concrete mixture containing 25% RCA
In general, the concretes with 25% RCA showed the same shrinkage behavior as the concretes made just with natural aggregate. Shrinkage increased continuously along time for the concretes with 10% RHA; the lowest shrinkage value was observed for the concretes without RHA [23].
One of the interesting results of the present work is the behavior of mixtures containing larger RHA amounts, which had lower shrinkage values, as observed in a previous study [18].
Mean shrinkage of mixtures containing 25% RCA and 10% RHA, at all ages, was approximately 46 μm higher than that of the 25% RCA and 0% RHA mixture. For the mixtures containing 25% RCA and 20% RHA, mean retraction was roughly 42 μm higher than that of the control mixture with 25% RCA, meaning an 8% reduction in shrinkage, compared with the mixtures containing 10% RHA.
Figure 8 presents the shrinkage curves and observed results for concretes with 50% RCA. The same behavior observed in Figure 7 is shown in Figure 8, but more intensely, with parallel curves for mixtures of all ages, and sharp decreases when 20% RHA was added.
One hypothesis to explain this behavior may lie in the reduction in total volume of voids in mixtures with 25% and 50% RCA and 20% RHA due to the lower percent amount of RHA added as admixture, when cement becomes more active [18]. RHA is an efficient pozzolan, and may reduce total porosity of concrete, changing the structure of pores and significantly reducing shrinkage.
Mean shrinkage of mixtures containing 50% RCA and 10% RHA, of all ages, was approximately 48 μm higher than that exhibited by the 50% RCA and 0% RHA mixture. The mixtures containing 50% RCA and 20% RHA exhibited shrinkage almost 18 μm higher than the value recorded for the control mixture, with 50% RCA. This means a reduction of 37.5% against the values observed for the mixtures with 10% RHA and 50% RCA.
The interaction between RHA and RCA became apparent, especially in terms of shrinkage of the 20% RHA and RCA mixture. However, more studies have to be conducted to better evaluate the interactions between RCA and RHA in mixtures at loner setting times and larger RHA contents, in order to confirm the hypotheses formulated.

Table 17
Compressive strength

Mixtures		Day 28 (MPa)	Day 63 (MPa)	Day 112 (MPa)
RCA (%)	RHA (%)			
0	0	24.4	26.3	27.0
0	10	26.6	31.4	31.4
0	20	29.1	29.3	31.5
25	0	20.4	19.4	22.6
25	10	22.9	28.8	34.3
25	20	23.3	32.7	36.9
50	0	25.0	30.6	30.2
50	10	27.1	31.4	30.1
50	20	30.5	32.4	35.5

3.5 Compressive strength

The average of the results of compressive strength are presented in Table 17. Figure 9 presents the graphic of the effect of the interaction between the factors RHA, RCA and W/B on the compressive strength, considering the average of all testing ages.
Teh compressive strength results corroborate in general the behavior showed in the capillary water absorption. The mixtures containing 10% RHA showed an increase in compressive strength in order of 5% comparing to concretes without RHA, and the use of 20% of RHA leads an increment around 9%. These results confirm the behavior of RHA as a pozzolanic material with good reactivity [2]. The observed increment in the compressive strength as the content of RHA is increased has been reported in several works [24], and it is attributed to a refinement of the pore structure. As in the literature the porosity analysed in the present work also can explain the compressive strength observed behavior.

4. Conclusions

The absorption rate of concrete mixtures, as a rule, diminishes with the addition of RHA and the same effect is observed for the concretes with RCA. In this work, when RCA and RHA were associated, absorption decrease considerably. In this sense, the interaction between RCA and RHA have a favorable effect, probably caused by the higher maximum size grain of RCA compared to the NCA and the fact that these larger grains contain more attached mortar with more porosity and higher water absorption. This high absorption leads the RCA to improving the transition zone and to decrease the available mixing water that promote the cement paste porosity. In the other hand, the RHA pozzolanic reaction reduces the porosity. The same effects were registered in the compressive strength behavior for the studied concretes.
Considering capillary porosity, the combined use of RCA and RHA had positive effect. Both admixtures reduced pores in mixtures, especially when these substances are used together.
The influence of RHA and RCA on total porosity was significant in all mixtures. The isolated effect of RHA was favorable, expressively reducing total porosity of mixtures. This reduction reached 50%, when compared with mixtures containing 20% RHA and 0% RCA.

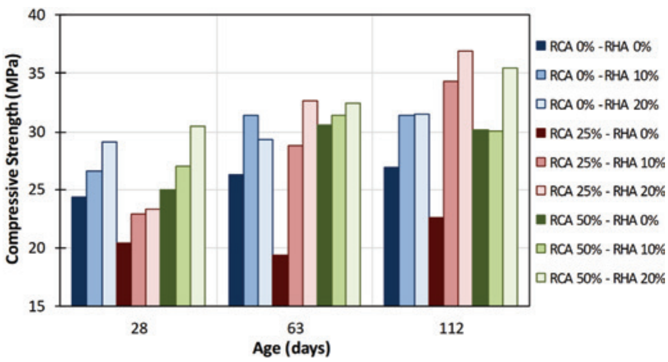

Figure 9
Compressive strength

Considering the influence of RCA and RHA in shrinkage in mixtures on days 1, 4, 7, 14, 28, 63, 91, and 112, the association of the two admixtures was significant, with an important change in behavior with increasing levels of RHA and RCA.
Initially, when 10% RHA was added to mixtures with 25% and 50% RCA, shrinkage values increased. Considering the hypothesis that RHA reduces pore size in mixtures without reducing total volume, it is possible to conclude that a larger the amount of small pores increases shrinkage.
Also, when 20% RHA is added to mixtures with RCA, shrinkage was observed to diminish. This may due to the fact that increasing RCA amounts improve the interaction between the pozzolan and the other components of the mixture, inducing a decrease in total volume of pores and therefore diminishing shrinkage when larger amounts are used.
In fact, the results show that the considerable interaction between RCA and RHA became apparent when 20% RHA is added to the concrete mixture with RCA.
More studies have to be carried out to measure these interactions and confirm the hypotheses.

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