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ULTIMATE SHRINKAGE MODELING OF RECYCLED AGGREGATE CONCRETE

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Abstract: *Data of recycled aggregate concretes shrinkage used to produce a linear model was proposed to predict the ultimate shrinkage. The fine and coarse recycled aggregates were made from crushed and sieved concrete, mortar and red ceramic. The proposed model shows the ultimate shrinkage of all recycled concretes are greater than the referential concrete. According to the proposed model, the recycled mortar fine aggregate is the most influential aggregate and the recycled mortar coarse is the less influential one in affecting the ultimate shrinkage of recycled aggregate concrete.*

Key Words: ***recycled aggregate concrete, shrinkage, modeling***

1. INTRODUCTION

The use of recycled aggregates in concrete production is a practice that is starting to become common in the technical field as a result of society pressure for environmental preservation, once with the use of the recycled aggregates, there is as a great economy of raw materials, as space in the dumps.

However, the use of that aggregate type produces some modifications in the behavior of the produced concretes, regarding some of the engineering properties. Among those properties, the shrinkage is the most modified one [1].

The concrete shrinkage is an inevitable phenomenon, since the environment where concrete is found has a relative humidity below saturation condition. As this is the condition that the great majority of concrete structures is found, shrinkage is one of the main causes of cracks, having a great importance in concrete durability.

It is known that the recycled aggregate use usually produces an increase in the concrete shrinkage, once these usually present a high water absorption, in function of the great tenor of mortar in those aggregates [2; 3; 4; 5].

The great majority of the reports about this subject presents the shrinkage performance after 56 days. However, it is known that the concrete continues to lose water to the exposed environment along its useful life. Therefore, it is necessary to determine the ultimate shrinkage of the recycled aggregate concrete for a better understanding of its behavior in service.

Hence, the objective of this paper is to model the ultimate shrinkage of recycled aggregate concretes based on the experimental results, using statistic and methematical tools.

2. EXPERIMENTAL PROGRAM

It was identified seven independent variables, which are: the fine and the coarse recycled aggregate of red ceramic, the fine and the coarse recycled aggregate of mortar, the fine and the coarse recycled aggregate of concrete and the water/cement ratio. Table 1 shows fine aggregates characteristics and Table 2 shows coarse aggregates characteristics, which were determined by Brazilian Standards.

Recycled concretes were produced using a design of experiments. The complete experimental design to study the total effect of all those 7 factors on the dependent variable is an experiment factorial design 2^k [6; 7]. The execution of that design consists in accomplishing 2^7 concrete mixtures, in other words, 128 mixtures. Due to time and cost limitations, the solution found to make the execution of the experimental phase possible, with high degree of reliability of results, was the use of the composed design of second order.

The base of the composed design of second order is a factorial design 2^k, fractional or complete, where it is added to this last one, all the 2^k vertexes of a star and the central points [6; 7]. For this experimental design, it was adopted a fractional factorial design and the central points. Table 3 shows the 50 mixtures used in this experimental program, which varies the content and the type of aggregate and the water/cement ratio.

Before making every concrete, a volume compensation of recycled aggregates was made because the simple replacement of the natural aggregates mass by recycled aggregates mass would result in mixtures with larger volumes of recycled aggregates, once the specific gravity of the recycled aggregates is smaller than the specific gravity of the natural ones, thus demanding more water and cement to produce equivalent mixtures to the mixture with natural aggregates.

The recycled aggregates were moistened 10 minutes before the mixture, with 80% of the water that would be absorbed in 24 hours by the recycled aggregate mass. This procedure was necessary in order not to modify the water/cement ratio by using the recycled aggregates.

The type V-ARI (according to Brazilian Standards) cement was used.

Table 1 *Fine aggregates characteristics.*

	Method		
	NM 30/00	NBR 9776/87	NM 45/02
Aggregate type	Absorption (%)	Specific Gravity	Bulk Density (kg/m^3)
Natural	0.42	2.64	1,440
Recycled concrete	7.55	2.56	1,540
Recycled mortar	4.13	2.60	1,440
Recycled red ceramic	10.69	2.35	1,460

Table 2 *Coarse aggregates characteristics.*

	Method		
	NM 53/02	NM 53/02	NM 45/02
Aggregate type	Absorption (%)	Specific Gravity	Bulk Density (kg/m^3)
Natural	1.22	2.87	1,560
Recycled concrete	5.65	2.27	1,430
Recycled mortar	9.52	2.01	1,390
Recycled red ceramic	15.62	1.86	1,260

Table 3 *Concrete mixtures defined according to the design of experiments.*

Mix	w/c	% of coarse aggregate				% of fine aggregate			
		N.	C	RC.	M	N.	C	RC.	M
01	0.46	100	0	0	0	100	0	0	0
02	0.74	100	0	0	0	0	0	100	0
03	0.74	100	0	0	0	0	100	0	0
04	0.46	100	0	0	0	0	50	50	0
05	0.74	0	0	0	100	0	0	0	100
06	0.46	0	0	0	100	0	0	50	50
07	0.46	0	0	0	100	0	50	0	50
08	0.74	0	0	0	100	0	33	33	33
09	0.46	0	0	100	0	0	0	0	100
10	0.74	0	0	100	0	0	0	50	50
11	0.74	0	0	100	0	0	50	0	50
12	0.46	0	0	100	0	0	33	33	33
13	0.74	0	0	50	50	100	0	0	0
14	0.46	0	0	50	50	0	0	100	0
15	0.46	0	0	50	50	0	100	0	0
16	0.74	0	0	50	50	0	50	50	0
17	0.46	0	100	0	0	0	0	0	100
18	0.74	0	100	0	0	0	0	50	50
19	0.74	0	100	0	0	0	50	0	50
20	0.46	0	100	0	0	0	33	33	33

Table 3 *Concrete mixtures defined according to the design of experiments – continuation.*

Mix	w/c	% of fine aggregate				% of fine aggregate			
		N	C	RC	M	N	C	RC	M
21	0.74	0	50	0	50	100	0	0	0
22	0.46	0	50	0	50	0	0	100	0
23	0.46	0	50	0	50	0	100	0	0
24	0.74	0	50	0	50	0	50	50	0
25	0.46	0	50	50	0	100	0	0	0
26	0.74	0	50	50	0	0	0	100	0
27	0.74	0	50	50	0	0	100	0	0
28	0.46	0	50	50	0	0	50	50	0
29	0.74	0	33	33	33	0	0	0	100
30	0.46	0	33	33	33	0	0	50	50
31	0.46	0	33	33	33	0	50	0	50
32	0.74	0	33	33	33	0	33	33	33
33	0.60	0	50	25	25	0	33	33	33
34	0.60	0	0	50	50	0	33	33	33
35	0.60	0	25	50	25	0	33	33	33
36	0.60	0	50	0	50	0	33	33	33
37	0.60	0	25	25	50	0	33	33	33
38	0.60	0	50	50	0	0	33	33	33
39	0.60	0	33	33	33	0	50	25	25
40	0.60	0	33	33	33	0	0	50	50
41	0.60	0	33	33	33	0	25	50	25
42	0.60	0	33	33	33	0	50	0	50
43	0.60	0	33	33	33	0	25	25	50
44	0.60	0	33	33	33	0	50	50	0
45	0.80	0	33	33	33	0	33	33	33
46	0.40	0	33	33	33	0	33	33	33
47	0.60	0	33	33	33	0	33	33	33
48	0.60	0	33	33	33	0	33	33	33
49	0.46	25	25	25	25	25	25	25	25
50	0.74	25	25	25	25	25	25	25	25

N: natural C: recycled concrete
RC: recycled red ceramic M: recycled mortar

For each concrete mixture, two specimens were molded and cured following the proceedings of *ASTM C 157- 93*. *ASTM C 490- 97's* method was used to measure the shrinkage in the specimens at 1, 3, 7, 14, 28, 56, 112 and 224 days of age.

The equation that describes the shrinkage behavior at the time is showed on Equation 1. As it can be seen, when time is too big, the *b* value is so small that can be ignored. So, the ultimate shrinkage is the *a* value.

$$\varepsilon_{sh} = \frac{a.t}{b+t} \quad (1)$$

Therefore, after the last measure, on day 224, the Equation 1 was parametrized through a linear equation (Equation 2) to find out the *a* value. Those *a* values were statistically analysed by a linear regression and a linear model (Equation 3) was proposed to predict the ultimate shrinkage of the recycled aggregate concretes.

$$\frac{t}{\varepsilon_{sh}} = \frac{1}{a}.t + \frac{b}{a} \therefore \; y = m.t + c \quad (2)$$

3. RESULTS

The results obtained for the 50 concrete mixtures shrinkages are shown in Figure 1. As it can be seen, all the mixtures with recycled aggregates had a greater shrinkage than the reference one.

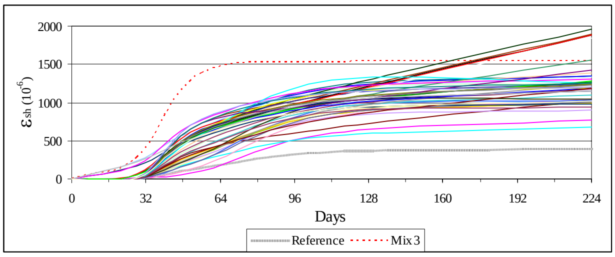

Figure 1 *Shrinkage behavior of all mixtures*

The results treatments were defined in agreement with the factorial design, which allows to test linear and quadratic terms. The accomplished tests also allowed to test linear and non linear models, for the dependent variables. For a better understanding of the model, it was made an name abbreviation of independent and dependent variables that are in Table 4.

Table 4. *Variables symbols used.*

symbol	variable	
	name	type
rmc	recycled mortar coarse aggregate	independent
rmf	recycled mortar fine aggregate	independent
rcc	recycled concrete coarse aggregate	independent
rcf	recycled concrete fine aggregate	independent
rrcc	recycled red ceramic coarse aggregate	independent
rrcf	recycled red ceramic fine aggregate	independent
w/c	water/cement ratio	independent
ε_{sh}	ultimate shrinkage	dependent

A linear data analysis was developed in a linear regression routine using all ultimate shrinkage data. Unfortunately, the model didn't show a good coefficient of determination because of the data variability. Some other complex models were tried but the coefficient of correlation didn't improve, so it was opted for the simplest model. The obtained model is described in Equation 3.

$$\begin{aligned} \varepsilon_{sh} &= (-23+1160.w/c)+ \\ &+(860.rcc+1010.rrcc+330.rmc)+ \\ &+(1330.rcf+835.rrcf+1805.rmf) \end{aligned} \quad (3)$$

In this model, the first part between parentheses models the ultimate shrinkage regarding to the water cement ratio. The second part between parentheses models the ε_{sh} regarding the tenor of recycled coarse aggregate replacement and the third part regarding the tenor of recycled fine aggregate replacement.

The percentage of fine or coarse aggregates replacement should be informed in the scale of 0 (0%) to 1 (100%), while the water/cement ratio is expressed in the usual scale, varying from 0.4 to 0.8. It should be observed that the sum of replacement percentile of natural aggregates by recyced ones should be 1 (100%) as a maximum value, for each aggregate type (coarse and fine).

4. DISCUSSION

Figure 2 and 3 present the concrete's ultimate shrinkage when the water cement ratio and the type of recycled aggregate are varied, for 50% and 100% of replacemement, respectively.

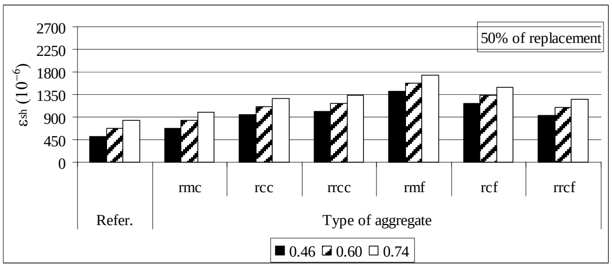

Figure 2 *Ultimate shrinakge regarding the water cement ratio and the aggregate type, for 50% of replacement*

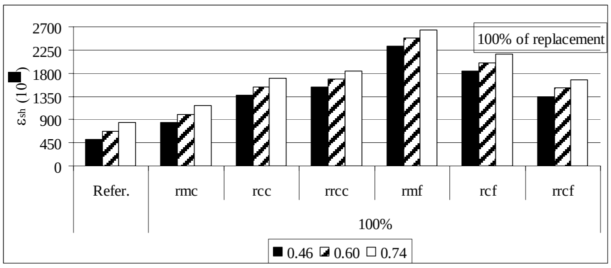

Figure 3 *Ultimate shrinakge regarding the water cement ratio and the aggregate type, for 100% of replacement*

It can be observed a variation in the ε_{sh} when the water cement ratio is modified. The greater the water cement ratio, the greater the ε_{sh}, once there is more available water in the concrete to be dried. According to the model, for a concrete without any recycled aggregate, an increase in the water cement ratio from 0.46 to 0.6 and to 0.76, increases the ε_{sh} in 32% and 64%, respectively.

For all types of recycled aggregates, the ε_{sh} increased when natural aggregate was replaced by them. When the tenor of replacement incresed, the ε_{sh} also increased. Such effect is coherent and it can be explained in function of the greater tenor of water demanded by the recycled aggregates before starting the mixures, once they have high absorption, producing higher porosity concrete than the reference [2; 3; 4; 5].

As it can be seen in the Figure 2 and 3, the concrete with recycled mortar fine aggregate had the worse performance, incresing the ε_{sh} in 2.8, 2.3 and 2.1 times for 50% of replacement and 4.5, 3.7 and 3.2 times for 100% of replacement for water cement ratio equal to 0.46, 0.6 and 0.74, respectively. This behavior is caused problably due to the high water absorption of this aggregate and the high content of cement paste.

The concrete with recycled concrete fine and coarse aggregate had also a great ultimate shrinkage probably due to the high tenor of mortar adhered to the natural aggregate. Once recycled concrete fine aggregate contains more mortar than recycled concrete coarse aggregate [5], it’s coherent that the ultimate shrinkage of concrete made with the first be higher than concrete's ultimate shrinkage made with the second one.

The best performance was obtained by the recycled mortar coarse aggregate, nevertheless the ε_{sh} was increased in 32%, 24% and 20% for 50% of replacement and 64%, 49% and 39% for 100% of replacement, for water/cement ratio equal to 0.46, 0.6 and 0.74, respectively.

However, the total effect of the water/cement ratio and the natural aggregate's substitution decreases when the water cement ratio increases. Table 5 and 6 show the ultimate shrinkage increases when varying the water/cement ratio and the replacement percentage of all recycled aggregates.

Table 5 *Increasing in ε_{sh} values when varying the water/cement ratio and the percentage of replacement of natural coarse agregates to recycled coarse aggregates*

		Recycled coarse aggregate					
		50%			100%		
w/c	Ref.	rcc	rrcc	rmc	rcc	rrcc	rmc
0,46	1,00	1,84	1,99	1,32	2,69	2,98	1,64
0,60	1,32	2,16	2,31	1,64	3,00	3,30	1,96
0,74	1,64	2,48	2,62	1,96	3,32	3,61	2,28

Table 6 *Increasing in ε_{sh} values when varying the water/cement ratio and the percentage of replacement of natural fine agregates to recycled fine aggregates*

		Recycled fine aggregate					
		50%			100%		
w/c	Ref.	rcf	rrcf	rmf	rcf	rrcf	rmf
0,46	1,00	2,30	1,82	2,77	3,60	2,63	4,53
0,60	1,32	2,62	2,14	3,09	3,92	2,95	4,85
0,74	1,64	2,94	2,45	3,40	4,24	3,27	5,17

Analyzing the data from Table 5 and 6, it can be noted that for high water cement ratios, the recycled aggregates influence less in the ε_{sh}, once there is already enough free water to enable higher shrinkages.

5. CONCLUSION

The replacement of natural aggregates by recycled ones, increased the ultimate shrinkage of all concretes. The greater the water cement ratio, the greater the ε_{sh}.The use of recycled fine aggregate provide the worst performance of recycled concretes, increasing 4.5, 3.7 and 3.2 times the ε_{sh}, for 100% of replacement, for water cement ratio equals to 0.46, 0.6 and 0.74, respectively. The best performance was obtained by the recycled mortar coarse aggregate, nevertheless the ε_{sh} increased in 1.64, 1.49 and 1.39, for 100% of replacement, for water cement ratio equals to 0.46, 0.6 and 0.74, respectively. The united effect of water cement ratio and natural aggregate's substitution decreases when the water cement ratio increases, once there is already enough free water to enable higher shrinkages.

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