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Performance Estimation for Concretes Made with Recycled Aggregates of Construction and Demolition Waste of Some Brazilian Cities

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The aim of this paper is to verify the influence of composition variability of recycled aggregates (RA) of construction and demolition wastes (CDW) on the performance of concretes. Performance was evaluated building mathematical models for compressive strength, modulus of elasticity and drying shrinkage. To obtain such models, an experimental program comprising 50 concrete mixtures was carried out. Specimens were casted, tested and results for compressive strength, modulus of elasticity and drying shrinkage were statistically analyzed. Models inputs are CDW composition observed at seven Brazilian cities. Results confirm that using RA from CDW for concrete building is quite feasible, independently of its composition, once compressive strength and modulus of elasticity still reached considerable values. We concluded the variability presented by recycled aggregates of CDW does not compromise their use for concrete building. However, this information must be used with caution, and experimental tests should always be performed to certify concrete properties.

Keywords: *CDW, waste variability, recycled aggregate, concrete*

1. Introduction

Due to improper managed, construction and demolition waste (CDW) has been causing severe problems to the population, once they are co-responsible for negative impacts, as inundations, because of the streams' siltation, damages to the landscape, obstruction of roads, proliferation of diseases, among other damages to the human health.

A point that demonstrates the relevance of CDW is its improvement in the urban solid wastes. Exemplifying, data from Salvador City, in Brazil, shows that from 1993 to 2000 the proportion of CDW on urban solid waste collected by the municipality[1] increased from 30.1% to 49.8%.

The same trend seems to hold in other regions of the world, once in Hong Kong the construction industry produces approximately 37,100 tons of wastes everyday, which corresponds to four times the volume of domestic wastes[2].

Several researches point that CDW are now around 50% of the urban solid wastes produced in Brazilian cities, with an average generation around 0.52 tons/inhabitant.year[3-6]. In European Union, there is no consensus about CDW generation but it represents approximately 22%-49% of the total waste generation at European cities, totalizing 450-970 million tonnes of CDW generated per year, which corresponds to 0.9-2.0 tonne/inhabitant.year, in average[7-9]. However, France and Luxembourg generate 5.5 and 15 tonnes/inhabitant.year, respectively, Germany and Ireland generate between 2 and 4 tonnes/inhabitant.year, while the rest of the European countries generate between 0.2 tonnes/inhabitant.year (Norway) and 1.9 tonnes/inhabitant.year (United Kingdom)[9]. In the United States, the generation of CDW during 90^{th} years was 0.43 tonne/inhabitant.year[10] and in 2002 it was estimated as 2.0-2.57 tonnes/inhabitant.year[11].

One of the main characteristics of CDW is its heterogeneity. The composition of CDW depends on many variables, among which we highlight: the geographical area where it is produced, the season of the year, the type of construction, among others. When originated from construction sites, the waste composition depends on the work stage, once in the concrete casting stage there is a larger incidence of concrete fragments, steel and timber formwork, while in the completion stage there is a predominance of mortar, bricks, tiles and ceramic fragments[2]. In case of reform work, a larger incidence of ceramic materials, wood, natural rocks, glasses, metals and plastics are usual[12].

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In Brazil, it is considered that on average 65% of the CDW are mineral, 13% wood, 8% plastics and 14% other materials. Construction industry is responsible for the generation of 20% to 25% of CDW and the remaining percentage comes from reforms and of auto-constructions works[13].

For demolition works, waste characteristics also vary according to the structure to be demolished and the technique used. However, in a general way, demolition wastes consist of a high percentile of inert material, as brick, sand and concrete. Metals, wood, papers, glass, plastics and other materials also appear, but in smaller percentage[2].

Table 1 presents the composition of CDW for different Brazilian cities. It can be observed that for all cities mortar, concrete and ceramic material correspond together more than 60%. That proportion is similar on other regions of the world, once in Europe, those components still correspond to something around 50% of the total CDW[14]. In Malaysia, concrete and aggregates wastes and concrete and ceramic blocks correspond to 67% of wasted materials[15] while in Kuwait, concrete debris and ceramic blocks correspond to 60%[16].

A research accomplished in agreement by eleven Brazilian universities measured the losses of construction materials in almost a hundred construction sites. Results of this research confirm values mentioned previously, once on average, 9% of pre-cast concrete, 17% of blocks and bricks, 85.5% of cement in plaster services, 79% of cement in underlayment services, 22% of ceramic plates to floors, 16% of ceramic plates to walls and 12% of ceramic plates to facade were wasted[23].

The data mentioned previously showed concrete, mortar and ceramic materials as the main components of construction wastes. Those data confirm the Brazilian constructive culture, where the largest losses happen in concrete casting, brickwork, plastering and covering. These materials are also the most wasted in construction sites of European Union. According to Van Acker[24], the mineral part of European CDW is composed approximately by 41% of concrete, 40% of masonry and 7% of ceramic and tiles.

In some urban areas there is a critical shortage of natural aggregates for concrete production, and, at the same time, in these areas there is an increase of CDW volumes. The recycling of CDW and its reuse in construction as an alternative raw material is a solution for the many problems it may represent and also for a reduction of the extraction of natural aggregates[25,26].

However, CDW composition variability has been pointed out as one of the restrictive factors for CDW recycling expansion, since the composition influences recycled aggregate concretes' performance.

In this context, the objective of this article is to verify the influence of composition variability of recycled aggregate of CDW in the performance of concretes, evaluated through its compressive strength, modulus of elasticity and drying shrinkage.

2. Research Method

Modeling the behavior of concrete properties, such as compressive strength, modulus of elasticity, tension strength, among other, already was a study object of some researchers[19,22,27]. However, the models proposed by such authors are specific for some composition and do not contemplate the natural variability of CDW.

In this study, to consider the variability a fractional project of experiments[28] was carried out. Factors under investigation (independent variables) were type and content of fine aggregate (natural, recycled mortar, recycled concrete and recycled red ceramic), type and content of coarse aggregate (natural, recycled mortar, recycled concrete and recycled red ceramic) and water/cement ratio (0.46, 0.60 and 0.74). Similar studies employing statistical tools were also conducted by other researches[22,27,29].

For this study, 50 concretes mixtures were prepared (see Table 2) and for each mixture seven cylindrical specimens (∅=10 cm; h = 20 cm) and two prismatic specimens (7,5 cm × 7,5 cm × 32,5 cm) were casted. Cylindrical specimens were used to evaluate compressive strength (f_c) and initial tangent modulus of elasticity (E_c) at 28 days of age, while prismatic specimens were used for testing drying shrinkage (ε) at 224 days of age. The tests were performed following the standard procedures NBR 5739[30], NBR 8522[31] and ASTM C 157[32], respectively. Average results for each property are also shown in Table 2.

Results were statistically analyzed using Statistica package 7.0 and models were built for each property. Nonlinear regression was used for building the models, which are presented in Equations 1, 2 and 3. Table 3 shows the terminology for independent and dependent variables used in models. Terms *b1*, *b2*, *a1*, *a2*, *a3*, *a4*, *a5* and *a6* are parameters estimated by the nonlinear regression routine.

Table 1. CDW composition observed in some Brazilian cities.

Components	São Carlos/SP[17] (%)	São Paulo/SP[18] (%)	Porto Alegre/RS[19] (%)	Ribeirão Preto/SP[20] (%)	Salvador/BA[1] (%)	Campina Grande/PB[21] (%)	Maceió/AL[22] (%)
Mortar	63.67	25.2	44.2	37.4	53.0	28	27.82
Concrete	4.38	8.2	18.3	21.1		10	18.65
Ceramic materials	29.09	29.6	35.6	20.8	9.0	34	48.15
Polished ceramic	0.39	-	0.1	2.5	5.0	1	3.06
Rocks, Soils	0.13	32	1.8	17.7	27.0	9	-
Others	2.34	5	-	0.5	6.0	18	2.32

Table 2. Concrete mixtures contemplated by the fractional factorial experiment and corresponding average values for compressive strength, modulus of elasticity and drying shrinkage results.

Mix	w/c ratio	Coarse aggregate (%)				Fine aggregate (%)				$f_{c,m}$ (MPa)	$E_{c,m}$ (GPa)	$\varepsilon_{224,m}$ (10^{-6})
		N	RC	RRC	RM	N	RC	RRC	RM			
01	0.46	100	0	0	0	100	0	0	0	46.13	34.47	393
02	0.74	100	0	0	0	0	0	100	0	34.42	20.62	777
03	0.74	100	0	0	0	0	100	0	0	17.78	15.14	1538
04	0.46	100	0	0	0	0	50	50	0	47.69	29.06	675
05	0.74	0	0	0	100	0	0	0	100	15.73	11.85	1387
06	0.46	0	0	0	100	0	0	50	50	31.11	16.70	1037
07	0.46	0	0	0	100	0	50	0	50	25.96	15.31	1345
08	0.74	0	0	0	100	0	33	33	33	19.12	14.47	1340
09	0.46	0	0	100	0	0	0	0	100	24.13	13.47	1096
10	0.74	0	0	100	0	0	0	50	50	18.62	11.83	1338
11	0.74	0	0	100	0	0	50	0	50	14.67	10.64	1246
12	0.46	0	0	100	0	0	33	33	33	26.88	12.61	1006
13	0.74	0	0	50	50	100	0	0	0	18.34	15.42	1000
14	0.46	0	0	50	50	0	0	100	0	35.48	15.83	1040
15	0.46	0	0	50	50	0	100	0	0	30.12	16.29	900
16	0.74	0	0	50	50	0	50	50	0	19.33	14.28	1384
17	0.46	0	100	0	0	0	0	0	100	30.47	20.26	1030
18	0.74	0	100	0	0	0	0	50	50	17.56	16.88	1101
19	0.74	0	100	0	0	0	50	0	50	14.60	14.86	998
20	0.46	0	100	0	0	0	33	33	33	39.01	21.18	998
21	0.74	0	50	0	50	100	0	0	0	19.40	18.07	749
22	0.46	0	50	0	50	0	0	100	0	42.18	18.69	881
23	0.46	0	50	0	50	0	100	0	0	33.65	21.66	1004
24	0.74	0	50	0	50	0	50	50	0	19.05	15.01	1242
25	0.46	0	50	50	0	100	0	0	0	34.78	21.15	985
26	0.74	0	50	50	0	0	0	100	0	26.03	14.39	1560
27	0.74	0	50	50	0	0	100	0	0	16.79	13.18	1956
28	0.46	0	50	50	0	0	50	50	0	35.13	18.70	1051
29	0.74	0	33	33	33	0	0	0	100	14.67	12.06	1892
30	0.46	0	33	33	33	0	0	50	50	31.11	17.12	1171
31	0.46	0	33	33	33	0	50	0	50	27.23	16.64	1243
32	0.74	0	33	33	33	0	33	33	33	18.62	14.15	1881
33	0.60	0	50	25	25	0	33	33	33	25.04	16.77	1845
34	0.60	0	0	50	50	0	33	33	33	23.42	14.51	1882
35	0.60	0	25	50	25	0	33	33	33	23.70	13.07	1278
36	0.60	0	50	0	50	0	33	33	33	25.96	16.68	1192
37	0.60	0	25	25	50	0	33	33	33	23.49	16.21	1190
38	0.60	0	50	50	0	0	33	33	33	24.90	16.00	1309
39	0.60	0	33	33	33	0	50	25	25	23.63	16.12	1257
40	0.60	0	33	33	33	0	0	50	50	26.10	15.62	1186
41	0.60	0	33	33	33	0	25	50	25	26.59	14.98	1267
42	0.60	0	33	33	33	0	50	0	50	23.56	16.24	1145
43	0.60	0	33	33	33	0	25	25	50	23.35	15.85	1243
44	0.60	0	33	33	33	0	50	50	0	27.86	15.68	1424
45	0.80	0	33	33	33	0	33	33	33	17.35	13.55	1253
46	0.40	0	33	33	33	0	33	33	33	36.54	19.70	1152
47	0.60	0	33	33	33	0	33	33	33	23.77	15.54	1224
48	0.60	0	33	33	33	0	33	33	33	21.22	16.16	1202
49	0.46	25	25	25	25	25	25	25	25	34.85	21.07	944
50	0.74	25	25	25	25	25	25	25	25	19.05	16.04	1015

N: natural aggregate; RC: recycled concrete aggregate; RRC: recycled red ceramic aggregate; RM: recycled mortar aggregate.

Table 3. Terminology for model variables.

Term	Variable	
	Description	**Type**
rmc	percentage of natural coarse aggregate replaced by recycled mortar coarse aggregate	Independent
rmf	percentage of natural fine aggregate replaced by recycled mortar fine aggregate	Independent
rcc	percentage of natural coarse aggregate replaced by recycled concrete coarse aggregate	Independent
rcf	percentage of natural fine aggregate replaced by recycled concrete fine aggregate	Independent
rrcc	percentage of natural coarse aggregate replaced by recycled red ceramic coarse aggregate	Independent
rrcf	percentage of natural fine aggregate replaced by recycled red ceramic fine aggregate	Independent
w/c	water/cement ratio	Independent
f_c	compressive strength at 28 days	Dependent
E_c	modulus of elasticity at 28 days	Dependent
ε_{224}	drying shrinkage at 224 days	Dependent

$$f_c = \left(\frac{b_1}{b_2^{w/c}}\right).\left[1-(a_1.rmc + a_2.rmf + a_3.rcc + a_4.rcf + a_5.rrcc + a_6.rrcf)\right] \quad (1)$$

$$E_c = \left(\frac{b_1}{w/c^{0,5}}\right).\left[1-(a_1.rmc + a_2.rmf + a_3.rcc + a_4.rcf + a_5.rrcc + a_6.rrcf)\right] \quad (2)$$

$$\varepsilon_{224} = \left(b_1.w/c^{0,5}\right).\left(1 + a_1.rmc + a_2.rmf + a_3.rcc + a_4.rcf + a_5.rrcc + a_6.rrcf\right) \quad (3)$$

Tables 4, 5 and 6 show parameter estimation for each regression model and the corresponding analysis of variance (ANOVA).

The coefficient of determination (R^2) computed by ANOVA indicates that models explain 96.5%, 96.6% and 60.4% of the variability observed in compressive strength, modulus of elasticity and drying shrinkage, respectively. Durbin-Watson statistics of all cases was superior to 1.4, which indicates that there are no serious problems of autocorrelation in the residuals. Once confidence intervals do not contain zero, it can be said that the terms included are significant considering the adopted confident levels.

Tests of normality of residuals were accomplished (Table 7), and in all cases the p-value was higher than 0.05, so the hypothesis of normal distribution can not be rejected at the 95% confidence level. Thus, usual hypotheses of regression analysis are satisfied.

Following the results of the statistical analyses, the models obtained for compressive strength, modulus of elasticity and drying shrinkage are shown in Equations 4, 5 and 6, respectively. These models were previously published by the authors[33,34].

$$f_c = \left(\frac{115}{7,2^{w/c}}\right).\left[1-(0,306.rmc + 0,164.rmf + 0,195.rcc + 0,058.rcf + 0,344.rrcc - 0,136.rrcf)\right] \quad (4)$$

$$E_c = \left(\frac{21}{w/c^{0,5}}\right).\left[1-(0,344.rmc + 0,150.rmf + 0,214.rcc + 0,098.rcf + 0,438.rrcc + 0,102.rrcf)\right] \quad (5)$$

$$\varepsilon_{224} = \left(675,4.w/c^{0,5}\right).\left(1 + 0,442.rmc + 0,766.rmf + 0,597.rcc + 1,05.rcf + 0,581.rrcc + 0,602.rrcf\right) \quad (6)$$

Finally, using the proposed models, a performance estimation of recycled aggregate concretes was accomplished. For that, the average composition of the recycled aggregates of the CDW for some Brazilian cities: São Carlos, São Paulo, Porto Alegre, Ribeirão Preto, Salvador, Campina Grande and Maceió, was used (see Table 1). However, there are some components in Table 1 that are not considered in the proposed models. To deal with this fact, components proportion was recalculated, excluding the materials that were not contemplated in the models. The new compositions of recycled aggregates of CDW, considering only mortar, concrete and ceramic material as components, are shown in Table 8.

Using the adjusted proportions, the values for each property (compressive strength, modulus of elasticity and drying shrinkage) were estimated using Equations 4, 5 and 6. Three concrete compositions were analyzed: concrete with 100% replacement of natural fine aggregate by fine recycled aggregates, concrete with 100% replacement of natural coarse aggregate by recycled coarse aggregates and concrete with 100% replacement of coarse and fine natural

Table 4. Parameter estimation and ANOVA for compressive strength.

Parameter	Estimator	Standard error	Confidence interval of 95% Lower	Upper
b1	115.12	5.445	104.12	126.11
b2	7.20	0.569	6.05	8.35
a1	0.306	0.028	0.249	0.361
a2	0.164	0.028	0.106	0.222
a3	0.195	0.028	0.138	0.251
a4	0.058	0.028	0.001	0.116
a5	0.344	0.027	0.291	0.398
a6	–0.136	0.030	–0.196	–0.074
ANOVA				
Source	**Sum of squares**	**Degrees of freedom**	**Mean square**	**F test**
Model	36272.9	8	4534.11	1692.5
Residual	109.828	41	2.678	
Total	36382.7	49		

R^2 = 96.50%; p-value associated to F test < 0.0001; Estimative standard error = 1.64; Durbin-Watson statistic = 1.98

aggregate for their respective recycled aggregates. Besides the aggregate type, the water/cement ratio (w/c) was varied, in values of 0.45, 0.60 and 0.75.

Table 5. Parameter estimation and ANOVA for modulus of elasticity.

Parameter	Estimator	Standard error	Confidence interval of 95% Lower	Confidence interval of 95% Upper
b1	21.03	0.369	20.282	21.770
a1	0.344	0.017	0.311	0.379
a2	0.150	0.018	0.114	0.186
a3	0.214	0.017	0.179	0.249
a4	0.098	0.017	0.063	0.133
a5	0.438	0.016	0.405	0.470
a6	0.102	0.016	0.069	0.135

ANOVA

Source	Sum of squares	Degrees of freedom	Mean square	F test
Model	13590.8	7	1941.54	3395.6
Residual	24.0143	42	0.572	
Total	13614.8	49		

R^2 = 96.60%; p-value associated to F test < 0.0001 ;Estimative standard error = 0.756; Durbin-Watson Statistic = 2.11

Table 6. Parameter estimation and ANOVA for drying shrinkage.

Parameter	Estimator	Standard error	Confidence interval of 95% Lower	Confidence interval of 95% Upper
b1	675.47	147.566	426.67	924.26
a1	0.442	0.282	0.034	0.918
a2	0.766	0.340	0.194	1.339
a3	0.597	0.313	0.069	1.125
a4	1.050	0.391	0.392	1.709
a5	0.581	0.302	0.072	1.089
a6	0.602	0.300	0.096	1.108

ANOVA

Source	Sum of squares	Degrees of freedom	Mean square	F test
Model	$6.07.10^7$	7	8683910	289.9
Residual	$1.13.10^6$	38	29956.8	
Total	$6.192.10^7$	45		

R^2 = 60.4% ;p-value associated to F test < 0.0001; Estimative standard error = 173.1; Durbin-Watson statistic = 1.77

3. Results and Discussion

The results of concrete performance estimation are shown in Figures 1, 2 and 3, for compressive strength, modulus of elasticity and drying shrinkage, respectively.

According to Figure 1, it is observed that w/c ratio and type of aggregate govern the compressive strength. The lower the w/c ratio, the higher the compressive strength, for all aggregate types. This result is coherent with other studies presented in literature[19,20,23,27]. Increasing the w/c ratio from 0.45 to 0.6 and to 0.75 promote 25.6% and 44.7% reduction in compressive strength, respectively.

Concrete with recycled fine aggregates showed the highest compressive strength among all analyzed concretes, reaching average values of 45.7 MPa, 34 MPa and 25.3 MPa, for w/c ratio of 0.45, 0.6 and 0.75, respectively. Using recycled coarse aggregates, concretes showed a 27.2% lower compressive strength, reaching average values of 33.2 MPa, 24.7 MPa and 18.4 MPa, for w/c ratio of 0.45, 0.6 and 0.75, respectively. The combined use of fine and coarse recycled aggregates provided concretes with similar strengths observed using coarse aggregate, around 30.8% lower compressive strength than the one observed using fine aggregate. Average compressive strength of 31.6 MPa, 23.5 MPa and 17.5 MPa, for w/c ratio of 0.45, 0.6 and 0.75, respectively, were reached.

According to Figure 2, modulus of elasticity and compressive strength behaviors were similar. The influence of w/c ratio and type of aggregate is also noticeable. As would be expected, the higher the w/c ratio, the lower the modulus of elasticity, for all aggregate types. An increase in w/c ratio from 0.45 to 0.6 and to 0.75 decreases modulus of elasticity in 13.4% and 22.5%, respectively. This behavior is coherent with other results presented in literature[19,27].

Concretes with natural coarse aggregate and recycled fine aggregate present a modulus of elasticity average values of 27.5 GPa, 23.8 GPa and 21.3 GPa, for w/c ratio of 0.45, 0.6 and 0.75, respectively. For concretes with recycled coarse aggregates and natural fine aggregates, the modulus of elasticity decreases 26.2%, reaching average values of 20.3 GPa, 17.6 GPa and 15.7 GPa, for w/c ratio of 0.45, 0.6 and 0.75, respectively. Using coarse and fine aggregates together, the average values of modulus of elasticity was 40.1% lower, reaching 16.5 GPa, 14.3 GPa and 12.8 GPa, for w/c ratio of 0.45, 0.6 and 0.75, respectively.

It can be observed that w/c ratio has less influence on modulus of elasticity than on compressive strength. It seems also that type of aggregate has a stronger influence in modulus of elasticity than w/c ratio, although the use of 100% of coarse aggregate promotes the same percentage

Table 7. Normality tests of residuals.

Test performed	Compressive strength: Test statistic	Compressive strength: *p* value obtained	Modulus of elasticity: Test statistic	Modulus of elasticity: *p* value obtained	Drying shrinkage: Test statistic	Drying shrinkage: *p* value obtained
Chi-Square goodness-of-fit	8.6734	0.89396	18.959	0.2155	13.8	0.541
Shapiro-Wilks W statistic	0.97497	0.54977	0.9607	0.1749	0.957	0.143
Z score for skewness	1.0176	0.30883	0.4944	0.6209	1.108	0.268
Z score for kurtosis	0.91226	0.36162	–0.1256	0.8999	1.562	0.118

reduction on compressive strength and on modulus of elasticity. However, the use of both fine and coarse recycled aggregate promotes a stronger reduction on the modulus of elasticity than on the compressive strength. This probably occurs due to the fact that the modulus of elasticity is mainly guided by the aggregate. As the recycled aggregate is more deformable than the natural aggregate, recycled aggregate concretes become more deformable than conventional concretes[20].

For drying shrinkage, it is again observed the influence of both w/c ratio and type of aggregate, as shown in Figure 3. Once drying shrinkage is linked with water loss, the higher the water content in concrete, the larger the drying shrinkage[20]. So, increasing w/c ratio from 0.45 to 0.6 and to 0.75 increases drying shrinkage in 15.5% and 29.1%, respectively.

Values obtained for concretes with recycled coarse aggregate are the smallest, presenting average values of 690, 797 and 891 micro for w/c ratio of 0.45, 0.6 and 0.75, respectively. Concretes with recycled fine aggregate showed shrinkage average values 15.8% larger, reaching 799, 923 and 891 micro for w/c ratio of 0.45, 0.6 and 0.75, respectively. For concretes combining fine and coarse recycled aggregate, drying shrinkage showed the greatest values, 50.1% larger than drying shrinkages of recycled coarse aggregate concrete, reaching average values of 1036, 1196 and 1337 micro for w/c ratio of 0.45, 0.6 and 0.75, respectively.

Since the water absorption of recycled aggregates is relatively high, put more recycled aggregates in concrete mixtures means that more water will be necessary to maintain the same workability. So it is coherent that

Table 8. Adjusted composition of recycled aggregates of CDW, considering only mortar, concrete and ceramic material as components.

Components	São Carlos (%)	São Paulo (%)	Porto Alegre (%)	Ribeirão Preto (%)	Salvador* (%)	Campina Grande (%)	Maceió (%)
Mortar	65.5	40	45.1	47.2	42.7	38.9	29.4
Concrete	4.5	13	18.6	26.6	42.7	13.9	19.7
Ceramic materials	30.0	47	36.3	26.2	14.6	47.2	50.9

*A percentage of 26.5% of concrete and 26.5% of mortar were used in the initial proportion.

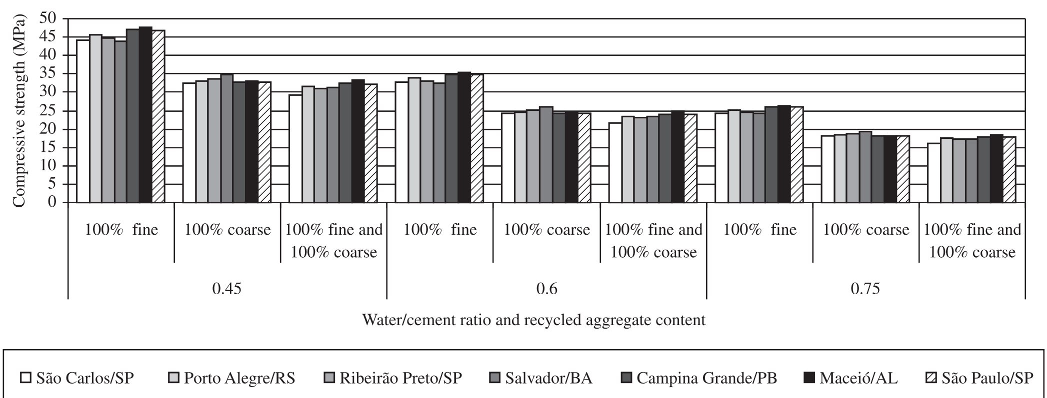

Figure 1. Compressive strength estimation for concretes with recycled aggregates of CDW of some Brazilian cities.

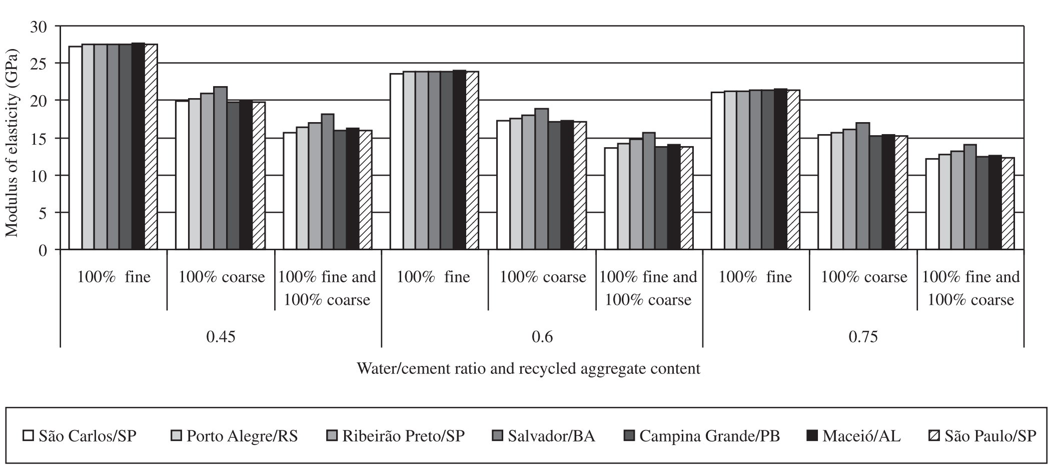

Figure 2. Modulus of elasticity estimation for concretes with recycled aggregates of CDW of some Brazilian cities.

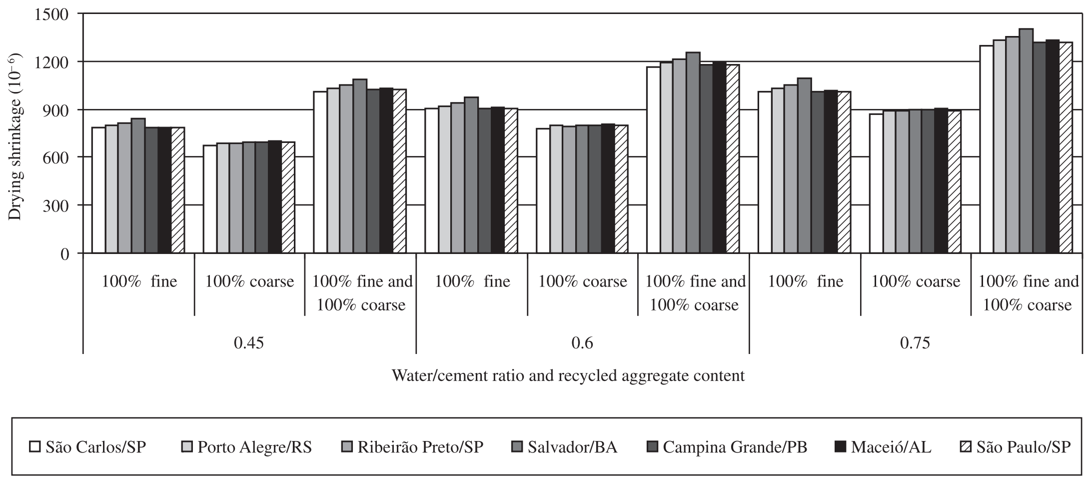

Figure 3. Drying shrinkage estimation for concretes with recycled aggregates of CDW of some Brazilian cities.

concretes with both fine and coarse recycled aggregate present the largest drying shrinkage.

For all analyzed properties, concretes with the same w/c ratio and type and content of recycled aggregate showed similar behavior, independently of the city where recycled aggregates comes from. However, analyzing the CDW composition of these cities, large variability is observed. Exemplifying, according to Table 4 data, mortar content in CDW varied from 29.4% in Maceió to 65.5% in São Carlos, while concrete content varied from 4.5% in São Carlos to 42.7% in Salvador, and ceramic material from 14.6% in Salvador to 50.9% in Maceió.

However, this pronounced variability does not have a strong influence in concrete properties. For example, according to Figure 1, comparing compressive strength of concretes with 100% of fine recycled aggregate and same w/c ratio, the maximum difference obtained among strengths (comparing among cities) is 9.2%. The same comparison for 100% coarse recycled aggregate and 100% fine and coarse aggregates reveals maximum differences on strength of 7% and 14.2%, respectively.

A similar analysis for the modulus of elasticity (Figure 2) reveals that the maximum differences obtained among cities for this property are 2.1%, 11% and 15.3%, for concretes with 100% of fine recycled aggregate, 100% of coarse recycled aggregate and 100% of fine and coarse aggregates, respectively. Finally, for drying shrinkage (Figure 3) the maximum differences obtained are 8%, 3.5% and 7.7%, for respectively concretes previously mentioned. This means that CDW composition, and consequently recycled aggregate composition, has little influence into compressive strength, modulus of elasticity and drying shrinkage of recycled aggregate concrete.

Although, it is worth noting that the estimation presented here were not experimentally proven. There are details concerning the used aggregates, like size distribution, absorption and density, and concerning used cement, like type and content of pozzolan or cement material, which are not contemplated by the proposed models. These are aspects that have influence on the measured properties. So, for project or building execution consideration, tests must be performed to assure the desired mechanical and durability concrete properties.

4. Conclusions

According to the results obtained using regression models to study the scenario of some Brazilian cities, we concluded that the use of recycled aggregates of CDW in concrete production is quite feasible. Compressive strength and modulus of elasticity of these concretes reached considerable values, mainly when fine recycled aggregate is used. Results reveal that the use of recycled aggregate should be prioritized into concretes with low w/c ratio, once it produces concretes with lower drying shrinkage, repressing fissures and increasing structure durability.

It was also noticed that the variability of recycled aggregate composition did not cause large differences in values obtained for compressive strength, modulus of elasticity and drying shrinkage. So, we concluded that the variability presented by recycled aggregates of CDW does not compromise their use for concrete building. However, this information must be used with caution, and experimental tests should always be performed to certify concrete properties.

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