Journal of Building Engineering 84 (2024) 108213

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Simple way to model the mechanical properties of concretes with recycled concrete aggregates

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ARTICLE INFO

Keywords:
Recycled concrete aggregates
Recycled concrete properties
Weighted water absorption
Effective water to cement ratio

ABSTRACT

Researchers have made efforts to model the mechanical properties of concretes with recycled aggregates joining large research databases. The replacement ratio criterion of natural aggregates by recycled ones has been widely used in the models, however, itself leads to a great dispersion of results and is inaccurate. In the manuscript, the weighted water absorption of both aggregates (coarse natural and recycled concrete one, *Ww*) and the effective water/cement ratio were used to easily predict accurately the porosity, compressive strength, and elastic modulus of the recycled concretes. For the modelling, a systematic review of the Brazilian studies from 1999 to 2020 was conducted compiling 169 concrete compositions and joined with 212 concrete mixes from international studies. A supplementary Excel file with the database and all existing correlations was provided. The 20%-replacement ratio limit of many standard codes for structural recycled concretes can be exceeded by using Ww < 5 % for structural concrete [40–60 MPa], or *Ww* < 8 % [25–40 MPa]. Aggregates with *Ww* > 8 % can be used for non-structural concretes, with little reduction in compressive strength in absolute terms (<5 MPa). The best %-replacement can be defined for each case, practical for concrete formulations in ready-mix companies.

1. Introduction

Researchers have made efforts to model the effects of recycled aggregates on the mechanical properties of concrete, but there is not yet a consensus on how to use it. The models are different in terms of the experimental database involved and the list of parameters required imposing limitations on their applicability or needing further improvements.

One of the first models used a single lot (average composition) of recycled aggregates from a real recycling plant but it indicated a %-replacement of natural aggregates by recycled ones (coarse, or fine) to make concrete strength or durability technically feasible [1]. After, other physical properties of recycled aggregates (water absorption, density and los angeles abrasion) were explored in a model and considered relevant to predict concrete strength [2].

Using large databases of concretes experimentally produced from 1980 to 2014, other authors [3–7] have explored the prediction of compressive strength, elastic modulus, and tensile strength of concretes using the replacement ratio of natural aggregates by recycled ones but always expressing the relative reduction in the mechanical properties of concrete in relation to an experimental

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https://doi.org/10.1016/j.jobe.2023.108213
Received 22 August 2023; Received in revised form 24 October 2023; Accepted 22 November 2023
Available online 5 December 2023
2352-7102/

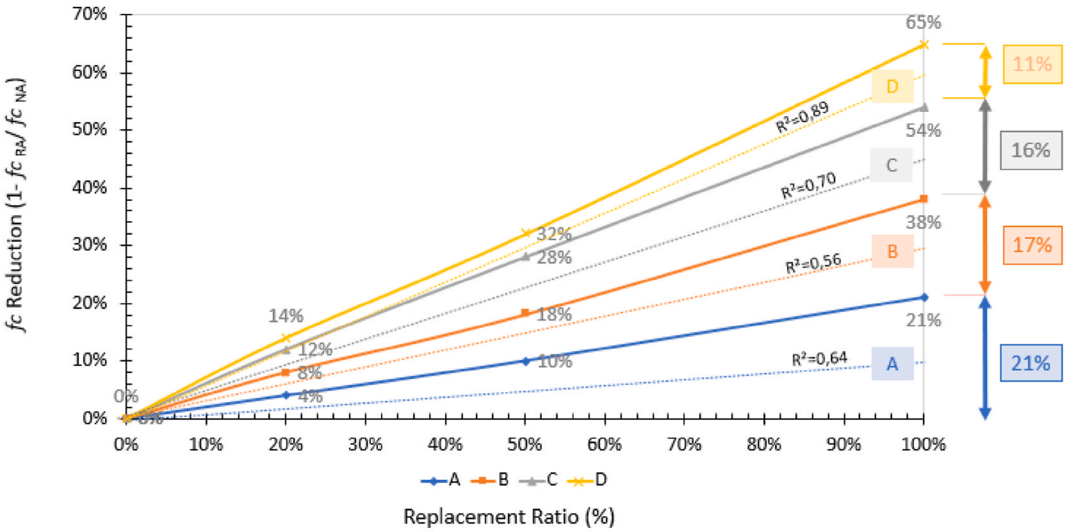
reference concrete, which contains only natural aggregates, fixed water-to-cement ratio, and cement and aggregate consumptions; therefore, it is not practical once it requires the establishment of a new relation for each new concrete formulation produced. The model also requires a classification of the recycled aggregates (*RA*) based on their water absorption and density into four distinct categories [3,8,9] (Fig. 1; adapted from Silva et al. [9]). Recycled concrete aggregate (*RCA*), the most homogeneous type is still significantly variable once the water absorption of the *RCA* can range from 2 % to 15 % [3,8,10–16] increasing uncertainty in the model prediction. These variations on *RCA* depend on factors such as the composition of the cementitious waste [17–19] (it may include mortar and other non-structural concrete wastes) and its respective porosities, usual in many countries like Brazil.

From the literature we know that the replacement of natural aggregates (*NA*) by recycled concrete aggregates (*RCA*) always reduces the compressive strength and elastic modulus of the recycled concretes [3,10,17,20–23] due to the greater porosity of the *RCA* compared to natural aggregate (*NA*) [17,24,25], without acceptable accuracy.

By standards, the partial replacement ratios of *NA* by *RCA* in structural concretes (above 20–25 MPa) need to be limited to a maximum of 25 % of the mass, including restrictions on the environmental exposure conditions [11,26–31], as well as on the aggregate composition (usually for only ceramic contents below 10 %). In fact, the classification of *RA* has less relevance at substitution levels below 20 %. It is understandable the limit adopted in international structural concrete standard codes in a conservative perspective. However, *RCA* with low porosity (with water absorption less than 3.5 %) cannot be used more than 20 % in mass, despite it could be almost totally incorporated, if the 10–20 % of reduction of the compressive strength is considered. Those simplifications limit the use of *RCA*.

On the other hand, when the substitution content exceeds 50 % of the mass it is essential to subcategorize the *RCA's* to ensure less variation in the recycled aggregate concrete property and its prediction by a modelling. For non-structural concretes (below <25 MPa) there is a neglectable reduction of the compressive strength (less than 5 MPa, absolute value) with high replacement ratios of *NA* aggregates by *RCA* [25,32]. Once the strength of cement paste is low, it makes the impact of the *RCA* less evident. Those recycled concretes are the most technically and economically viable because they have the greatest potential of *RCA* application in concrete; however, it will also require the subcategorization of *RAs*, and *RA* characterization tests (as composition, water absorption, density).

Other models to predict the mechanical properties of the recycled aggregate concrete exist. Pepe et al. [33], despite using a limited quantity of experimental studies proposed a model taking into consideration one single factor; the water absorption of the recycled concrete aggregate; and its change on the effective water-to-cement ratio (W/C_{ef}), and the W/C_{ef} effect on hydration degree of cement [23]. Indeed, *RA* absorbs part of the water from the cement paste [34] changing the water to cement ratio (W/C_{ef}) of concrete. Therefore, the W/C_{ef} must be determined to avoid the construction of an erroneous view that the recycled aggregate concrete may have a higher compressive strength (f_c) than concrete with natural aggregates, when analyzing only the total water/cement ratio of the mix proportioning. Pre-saturating the recycled aggregate between 60 and 90 % of its 24h-water absorption is a recommendation [27, 35–37], or adding this quantity of water calculated for pre-saturation to the total water used in the mixture (a water compensation strategy) [38]. Up to now, W/C_{ef} cannot be precisely determined; however, it plays an important role in the prediction of recycled concrete mechanical properties [3,8,23] since it represents the cement matrix strength. W/C_{ef} is a critical parameter; it has even more effect on concrete mechanical properties than the *RCA* replacement.



Aggregate Class	A	B	C	D
Minimum ODD (kg/m³)	2600 - 2400	2300 - 2100	2000 - 1800	No limit
Maximum Water absorpotion (%)	1.5 – 3.5	5 – 8.5	10,5 - 15	No limit

Fig. 1. Influence of the recycled aggregates on concrete with the same W/C_{ef} ratio. *ODD* means Oven Dry Density. $f_{c\ NA}$ mean compressive strength of reference concrete including only *NAs*, and $f_{c\ RA}$ mean compressive strength including different ratios of *RCA* (Adapted from Silva et al., 2014 [3]).

Pepe [23] also analyzed two other ways to model the mechanical properties of concrete using *RCA* using the Compressive Packing Model (CPM) [39] and the Lattice Model [40]. To estimate the compressive strength, the CPM model needs considering the cement matrix strength (estimated by its phases volume); the maximum paste thickness (MPT), which represents the distance between the aggregates within the concrete and involves the maximum diameter of aggregates; the packing density of aggregates and its volumes in concrete, as well as empirical constants from the interfacial zone between the cement paste and aggregates (ITZ) that is not fully studied or documented in the literature. The model is highly accurate, but it demands a more complete characterization of recycled aggregates, scarcely documented in literature, and it uses a software to estimate the packing density where shape of aggregates is regularly disregarded. The Lattice method [40] employs a computational approach to simulate fracture processes and needs ITZ information and some expertise. The methods are also suggested by France [8], but complexity limits its use.

González et al. [41] also improved the concrete mechanical properties model using the water absorption of the recycled aggregate and %-replacement using the largest database in literature ameliorating the models for elastic modulus and splitting tensile strength. Both properties of the recycled aggregates are, in fact mandatory. The relative reduction of elastic modulus of concretes containing *RCA* using only %-replacement parameter is significantly variable [22]. The review collected 1368 results dealing with concretes with water to cement ratio (*W/C)* [0.25–0.85] and compressive strength [15–135 MPa]. Other composites variables related to the volume of the phases and the respective elastic modulus (their constitutive properties) needs to be considered for accurate prediction [39,42] using a comprehensive physical and mechanical model. Fundamentally, the elastic modulus (*E*) of concrete is governed by its porosity [17,42]. Therefore, the elastic modulus of concrete depends on the elastic modulus of the cement paste, the elastic modulus of the aggregate, and their respective volumes in the mixture [24]. The higher the elastic modulus of the aggregates and the greater their volume, the higher the elastic modulus of concrete. Some prediction models for conventional concretes are presented in Ref. [42] following this rule.

Duan et al. [110] used artificial neutral networks using 146 concrete compositions to obtain a highly accurate model for mechanical properties of recycled aggregate concrete capturing the influence of 14 parameters of the mix designs, %-replacement in volume, and the properties of the recycled aggregates (water absorption, SSD density, impurities content, maximum size) and the natural aggregates (fineness modulus of sand). It is a future relevant research direction as proved by many other authors [43,44] using larger database, how to select the best algorithms [45], probabilistic-based method as Baysean one [46] trying to include other relevant mechanical properties, as shear strength and modulus which data from literature is still scarce [47]. The use of large database is mandatory, as well explore the use of many mix parameters and properties of the aggregates that cannot be fully captured in most of the studies.

Although many variables can be integrated into prediction models to enhance the accuracy of mechanical properties predicting, it is not always possible to include them suffering on data limitation in literature. While complex and precise models are intriguing, the simplest model with acceptable accuracy offer a practical guide to produce concrete experimentally.

1.1. Objective and research significance

The most used recycled aggregate parameter to model the mechanical properties of concrete is the replacement ratio of natural aggregates by recycled ones. However, this criterion leads to a great dispersion of results, and itself is inaccurate due to the variability of the water absorption of the recycled aggregates. Water absorption of the recycled aggregate needs to be integrated in the models.

In the manuscript, the weighted water absorption of both aggregates (coarse natural and recycled, *Ww*) and the effective water/cement ratio were used to predict accurately the porosity, compressive strength, and elastic modulus of the recycled concretes.

Using the weighted water absorption of both aggregates, the current limitation of 20 % of replacement ratio imposed by many standard structural codes, or general rules as 50%-replacement for non-structural concrete, can be exceed.

The model proposed herein is a simple way to predict mechanical properties of recycled aggregate properties based on the porosity contribution of the two major phases of the concrete (cement matrix, and aggregates) [21,39,42]; therefore, it contains a rational physical-mechanical theory behind. Other models are certainly more accurate than the proposed herein, however, those are less practical to orient concrete formulation and concrete in ready-mix plants.

Additionally, several academic studies in Brazil have been conducted over the last 20 years to evaluate the mechanical properties of concrete with recycled concrete aggregates (*RCA*) and many of them is not published in indexed scientific journals internationally acessible, which makes difficult is integration to international databases. Those data were systematized herein and it is now available as supplementary data, able to enhance future literature models.

2. Methodology

This research was conducted through a systematic review of the Brazilian literature on concrete produced with coarse *RCA* published between 1999 and 2020. A set of dissertations, theses, and articles were collected in databases of repositories of Brazilian federal and state universities by searching for the keywords (in Portuguese) “concrete with recycled aggregate”, “recycled concrete aggregate”, and “concrete with construction and demolition wastes”.

The criterion for inclusion in the analyses were as follows: (1) coarse *NA* replaced by coarse *RCA* in concrete mix; (2) the compressive strength of the concrete from 15 to 70 MPa; and (3) density or water absorption of the coarse *RCA* informed. Concretes that used fine recycled aggregate were not collected because of limited data and the lack of reliable water absorption measurements for recycled fine aggregate.

The selection criterion were met by eighteen Brazilian studies [25,37,48–62], totaling 169 distinct concrete mix proportions, called in this article Brazilian database (*BRA*).

The database were partially compared with international database (*INT*) previously collected by our research group [63]. It was compiled 27 studies [2,34,36,64–88] from international indexed journals and conferences from 1996 to 2018, adding up to 212 concrete proportioning mixtures containing *RCA*.

To sum up, it was registered 381 mixes in the supplementary excel file. Part of the international data used in this article (78 concrete mixtures from seven studies) was included in the analyses conducted by Silva et al. (2014) [3], done with 787 concrete mixtures from 65 publications; but, used the replacement ratio criteria. In this paper, we used an alternative parameter, the weighted water absorption for both aggregates types (*NA*, *RCA*).

The collected data were organized using symbols, abbreviations, and acronyms described in Appendix A(Table A.1).

A supplementary Excel data file containing the database of this study (381 concrete mixes, 13,000 data inputs) is available with this manuscript, as described in Table 1. An overview about the formulation of the recycled concretes and the range of properties investigated is presented in Table 2.

Once not all aggregate properties were reported [25,49,52,55,58,89], the mean values from other studies were adopted according to their natural aggregate origin (Table A.2, Appendix A). In a specific case [55], it was adopted a general mean value because the natural aggregate origin was not informed.

Recycled aggregate density presented significant differences. The oven-dry density (ASTM C 127 [90]) (including the internal pores of the particles) were used to calculate the aggregate volume in the concrete. The oven-dry density was estimated when the water absorption was only reported. An interrelationship presented in the appendix of ASTM C 127 was used for it.

The Brazilian studies present a wide extension of *RCA* (mixed cementitious waste sources, with more than 10 % of water absorption) and compressive strength of recycled concretes below 30 MPa, less investigated type when compared our data available internationally. In the best of our knowledge, our manuscript can also broaden the understanding about the modelling of recycled aggregate concrete mechanical properties.

2.1. Calculation of indices

The analyses followed the following steps: (A) data collection, (B) calculation of formulation parameters, and (C) analysis of correlations between parameters and indicators, as shown in Fig. 2.

Three main indices were calculated to evaluate the physical and mechanical properties of the recycled concretes: weighted water absorption of the aggregates, effective water to cement ratio and free water. The equations herein were proposed by the authors.

The effective water-cement ratio (W/C_{ef}) was calculated using Eq. (1). Q_W, Q_{NA}, Q_{RA}, Q_C, are the quantities of water, coarse *NA*, coarse *RCA,* and cement, respectively, in kg/m^3 of concrete. W_{NA} and W_{RA} are the 24h-water absorption (%) of the coarse natural and recycled aggregates, respectively.

$$W \Big/ C_{ef} = \frac{Qw \ - k\times(Q_{NA} \times W_{NA} + Q_{RA} \times W_{RA})}{Q_c} \quad \text{Eq. (1)}$$

Parameter *k* establishes the ratio of 24 h-water absorption that occurs in the first minutes of the concrete mixing procedure (see Eq. (2)). A sensitivity study was conducted by varying the k values between 0.5, 0.6, 0.7, and 0.8 [17,27,35] (see supplementary data, worksheet "Sensitivity analysis"). Then we established a k value of 0.7 to use in the correlations. Therefore, we used this value for all analyses presented. In Eq. (1), when the recycled aggregate was used in dry conditions at the mixing procedure, 0.7 of the weighted water absorption of aggregates (W_W) (Eq. (2)) was disregarded from the effective water to cement ratio calculation. A migration of water ($k = -0.3$) from the aggregates to the paste was considered when the aggregate was placed on saturated surface dry (*SSD)* [36].

The weighted water absorption of coarse aggregates (W_W) was calculated using Eq. (2).

$$W_w = \frac{(Q_{NA} \times W_{NA} + Q_{RA} \times W_{RA})}{Q_{NA} + Q_{RA}} \quad \text{Eq. (2)}$$

A "*Free Water"* Index (*FW*) was calculated to determine the quantity of water present in the concrete per m^3 (Eq. (3)), which produces capillary pores in the cement matrix and in the aggregates. The free water index did not include the combined water in the cement chemical reaction, but it included the water that was absorbed by the *RCA*. It represents the total concrete's porosity. A hydration degree of the cement (α index) was used to adjust the water that reacts chemically with cement, typically after 28 days. It was adopted 0.23 (maximum 0.27; 90 % hydration degree; the highest content of commercially available clinker Portland cement) [91] and 0.18 for cements with supplementary cementitious materials [92,93]. This parameter was based on the *combined water fraction* concept proposed by John et al. [94].

Table 1
Instructions to find the collected data in the supplementary materials.

Parameters	BRA DATA (Sheet "BRA valid data")	INT DATA (Sheet "INT data")
	See Columns	See Columns
Concrete mix proportions; quantity of cement, water, aggregates (kg/m^3)	P to AC	P to AC
Characteristics of aggregates	F to O	H to O
Characteristics of cement, and admixtures	AD to AH	AD to AH
Physical and mechanical properties of concrete	AW to AZ	AO to AQ

Table 2
Overview of collected data.

Variable	*BRA*				*INT*			
Quantity of Cement (kg/m^3)	*<300*	*300–350*	*350–400*	*>400*	*<300*	*300–350*	*350–400*	*>400*
Number of data	18	24	40	59	19	60	75	58
%	13 %	17 %	28 %	42 %	9 %	28 %	35 %	27 %
Quantity of water (kg/m^3)	*<170*	*170–200*	*200–220*	*>220*	*<170*	*170–200*	*200–220*	*>220*
Number of data	10	58	56	17	76	94	26	16
%	7 %	41 %	40 %	12 %	36 %	44 %	12 %	8 %
Effective Water to cement ratio (see Eq. (1) at topic 2.1)	*<0.4*	*0.4–0.5*	*0.5–0.65*	*>0.65*	*<0.4*	*0.4–0.5*	*0.5–0.65*	*>0.65*
Number of data	18	42	59	22	20	84	92	16
%	13 %	30 %	42 %	16 %	9 %	40 %	43 %	8 %
Quantity of Fine Aggregates (kg/m^3)	*<675*	*675–800*	*800–900*	*>900*	*<675*	*675–800*	*800–900*	*>900*
Number of data	26	62	31	21	78	98	28	8
%	19 %	44 %	22 %	15 %	37 %	46 %	13 %	4 %
Quantity of Coarse Aggregates (NA + RCA) (kg/m^3)	*<800*	*800–900*	*900–1000*	*>1000*	*<800*	*800–900*	*900–1000*	*>1000*
Number of data	32	30	31	48	11	17	27	157
%	23 %	21 %	22 %	34 %	5 %	8 %	13 %	74 %
Replacement Ratio	*0–25 %*	*25–50 %*	*50–75 %*	*>75 %*	*0–25 %*	*25–50 %*	*50–75 %*	*>75 %*
Number of data	48	23	20	50	85	28	33	66
%	34 %	16 %	14 %	35 %	40 %	13 %	16 %	31 %
Weighted water absorption (see Eq. (2) at topic 2.1)	*<2 %*	*2–5%*	*5–8%*	*>8 %*	*<2 %*	*2–5%*	*5–8%*	*>8 %*
Number of data	66	38	22	15	72	140	44	1
%	47 %	27 %	16 %	11 %	28 %	54 %	17 %	0 %
Slump (some data uninformed)	*<50*	*50–100*	*100–150*	*>150*	*<50*	*50–100*	*100–150*	*>150*
Number of data	6	65	27	19	13	33	32	15
%	5 %	56 %	23 %	16 %	14 %	35 %	34 %	16 %
Cement strength class (MPa) (some data uninformed)	–	*32*	*42*	*52*	–	*32*	*42*	*52*
Number of data	0	76	65	0	52	18	53	89
%	0 %	54 %	46 %	0 %	25 %	8 %	25 %	42 %
Concrete Compressive Strength (MPa)	*<25*	*25–35*	*35–45*	*>45*	*<25*	*25–35*	*35–45*	*>45*
Number of data	24	58	40	17	10	73	81	48
%	17 %	42 %	29 %	12 %	5 %	34 %	38 %	23 %
Elastic Modulus (GPa) - (some data uninformed)	*<25*	*25–30*	*30–35*	*>35*	not collected			
Number of data	13	16	21	11				
%	21 %	26 %	34 %	18 %				

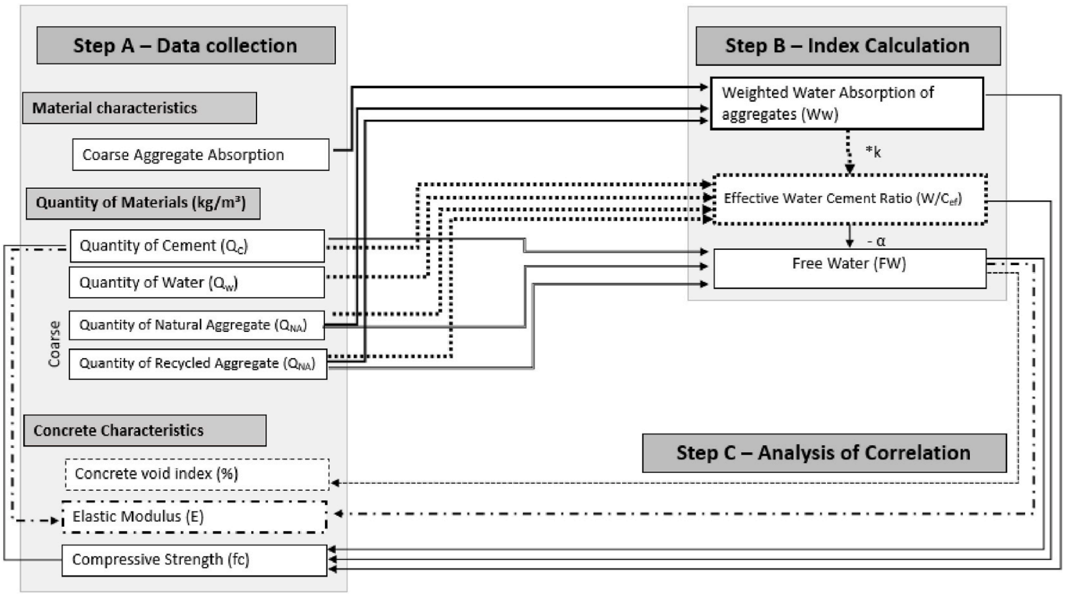


Fig. 2. Flowchart of the main collected data, calculation indices and analysis of correlations.

$$FW = \frac{\left(W/C_{ef} - \alpha\right) \times Q_C + W_w \times (Q_{NA} + Q_{RA})}{1000} \quad \text{Eq. (3)}$$

All concrete specimens in the Brazilian data were cylindrical (10 × 20 cm). Some international data also used cylindrical specimens, while others used cubic specimens. In these cases, the cube compressive strength was converted and compared to cylindrical specimens by multiplying the compressive strength by 0.8 [95].

2.2. Correlations

The supplementary excel file contains all data correlations and the modelling basis presented herein.

For the Brazilian data, 28 concrete mixtures were disregarded due to the differences in the informed density and in the expected density (in kilos per one cubic meter), calculated with the quantity and density of each material, when differences are greater than 5 %. Most of mixtures did not provide the air-entrained volume in the fresh concrete; so, this parameter was disregarded from the density estimation. Usually, there is up to 5 % air-entrained in recycled concrete, almost the double (~2 % v/v) of the conventional concrete (with natural, non-porous aggregates); that is why 5 % of difference was considered admissible and it may lead to slight dispersion in the density results. Therefore, we included 141 of 169 Brazilian concrete mixtures. In the mixes not included, the informed volume did not reach 100 % probably due to mistakes such as the informed quantities of materials, errors in the density tests, or approximations. This analysis was not made for the international data (*INT*) once we did the collect in our previous study.

The quantity of data used for the correlations is not the same because there is missing information. e.g., only 61 of the 141 Brazilian *(BRA)* concrete mixtures were tested for elastic modulus. Therefore, the correlations constructed may contain variable quantity of data in.

To produce the correlations and the regression tendency lines with the mechanical properties, the data were grouped in distinct categories of effective water to cement ratio, or weighted water absorption of aggregates to obtain the best coefficient of correlation (R^2). The procedure did not affect the physical and mechanical principles used herein; the porosity is governing the mechanical properties, and it has two influencing factors: the aggregate porosity, and the cement matrix porosity.

In some cases, outlier values were observed and not included in the correlations when statistically representing less than 10 % of the data population. Those are shown in the graphs and figure captions labeled as outliers, "*OL*".

Cement strength classes (with a minimum of 32.5, 42.5 MPa) were considered in the analyses and grouped as ($f_{pc,min}$, *32 MPa*) and ($f_{pc,min}$, *42 MPa*), where most Brazilian data were concentrated and integrated with the equivalent cement strength class of the international data (*INT*). Because of high dispersion and limited data availability, analyses of the cement strength class ($f_{pc,min}$, *52 MPa*) (with a minimum of 52 MPa) were not performed in the manuscript. Differences in cement strength occur owing to the specimens' shapes (cubic, cylinder) and water to cement adopted in the standard test. However, those changes are insufficient to change the global trends in cement minimum strength categories.

Despite the well-established fact that the *RCA* negatively affect the workability of concrete [35–37,71], a model to describe sufficiently the influence of its constituents (recycled aggregate, cement, water, additive) cannot be obtained. The reasons are.

1) Slump test cannot describe the rheological behavior of concrete [96]. To measure rheological properties, a rheometer is required evaluating yield stress and viscosity o the suspensions in multiple shear rate points.
2) Many properties of the particulate materials like the particle size distributions of all aggregates, those of the cement and SCMs, the shape parameters, packing density measurements (or models), a surface area determination, and density are required for a model

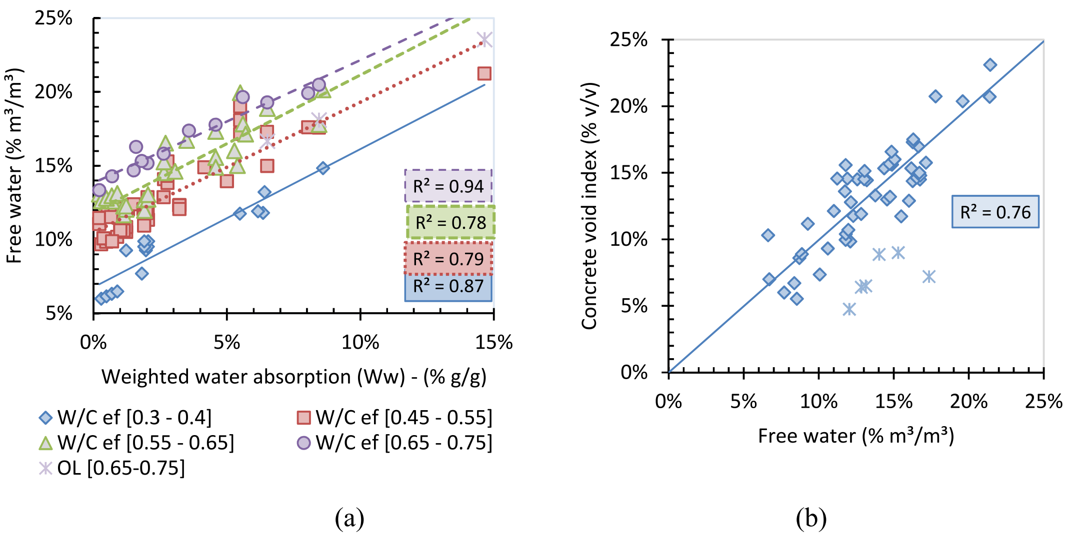


Fig. 3. (A) *Free water* vs. W/C_{ef} vs; W_W. 118 BRA results. 4 OLs from Refs. [25,49,57] (b) *FW* vs. Concrete Void Index. 57 BRA results. 6 OLs from Refs. [65,69].

development [39,97,98]. The humidity of the aggregates (natural, recycled ones) needs to be controlled [99] because it will affect the effective water-to-cement ratio and the kinetics of water migration between aggregates and paste is not fully understood.

3) We attempted to model the workability using concepts such as the effective water/cement ratio (W/C_{ef}) and particle separation distance in suspension (IPS and MPT [100–104]). Those parameters including the presence of dispersant additives was significant for the model but the data provided (here in the supplementary excel file, or the measurements range presented in Table 2) was insufficient to obtain complete or accurate correlations. Therefore, those will not be presented in the manuscript.

3. Results and discussions

3.1. Porosity

The volume of concrete is equal to the sum of the volumes of its constituents. Therefore, the cement paste volume increases as the aggregate volume decreases (see Appendix B, Fig. B2), and an increase in the volume of the cement or water increases the paste volume. In recycled concrete, a non-negligible portion of the added water is absorbed by the recycled aggregates, thereby changing the paste volume. Furthermore, it was considered the effective remaining water ($Q_{W;}$ l/m^3) in the paste when calculating the parameters that control several properties in hardened state. The impact of water absorption in the W/C_{ef} is presented in appendix C.

The *Free Water* of concrete (*FW*), as calculated according to Eq. (3), includes all water inside the concrete that does not participate in the chemical reaction of cement, both inside the paste and inside the aggregates. Therefore, both weighted water absorption of aggregates (*Ww*) and W/C_{ef} are related to free water (*FW*) (Fig. 3a). Fig. 3b presents the relationship between the calculated free water (*FW*) and concrete *void index* (test performed according to NBR 9778 (ABNT, 2005)) [105]. The Free water indirectly represents the total void volume of the concrete. For a similar W/C_{ef}, W_W is a determining factor for the increase in free water (and porosity) of recycled concrete.

3.2. Elastic modulus

The elastic modulus of concrete depends on free water (which express the total porosity) (Fig. 4), i.e., the sum of the porosities of the aggregates and cement paste. The free water is significantly affected by the weighted water absorption of the aggregates, W_W (Fig. 3a). In fact, according to the literature, porosity of the aggregate significantly reduces the elastic modulus of concrete (*E*) [42]. An increase in the quantity of cement (*Qc*) slightly reduces the elastic modulus of the concrete, since the modulus of the paste is smaller than that of the aggregate, according to the literature models [42].

3.3. Compressive strength

As seen in Fig. 1, the use of the replacement ratio criterion may lead to a great dispersion in the prediction model of recycled aggregate concrete strength. Fig. 5 illustrates how an increase in the replacement ratio of *NA* by *RCA* increases the weighted water absorption (W_W) of the coarse aggregates used in the concrete. For the same replacement ratio, W_W can increase by up to five times, depending on the *RCA* absorption. For instance, the same *Ww* [4 %] can be obtained with a replacement ratio of 30 % for a high W_{RA} [>7 %] or up to 100 % for a lower W_{RA} [3–5%]. Furthermore, the higher the replacement ratio, the greater is the influence of the water absorption differences between different recycled aggregates. The three Brazilian (*BRA*) datasets with extremely high *Ww* [14.6 %] was obtained using a density separation process in aggregates [25]. The 9 Brazilian (*BRA*) data with *Ww* [8.4–8.6 %] were obtained from the crushing of low-strength concretes [15–18 MPa] [63], and [67].

The model based on replacement barely predicted the compressive strength of concrete (Appendix B, Fig. B1.) without the implementation of *RCA* subcategories. The factor that governs the porosity (and strength) of concrete is not only the replacement ratio of *NA to RCA* but also the intrinsic porosity of *RCA* (which depends on its source). Therefore, weighted water absorption needs to be used (Fig. 6).

Fig. 6 shows how *Ww, W/C*$_{ef}$, and the cement compressive strength class ($f_{pc,min}$ [32 MPa], the left chart, $f_{pc,min}$ [42 MPa], at the right) affects the concrete compressive strength (f_c). The blue trend line [<2 %] represents the concretes made with natural aggregates

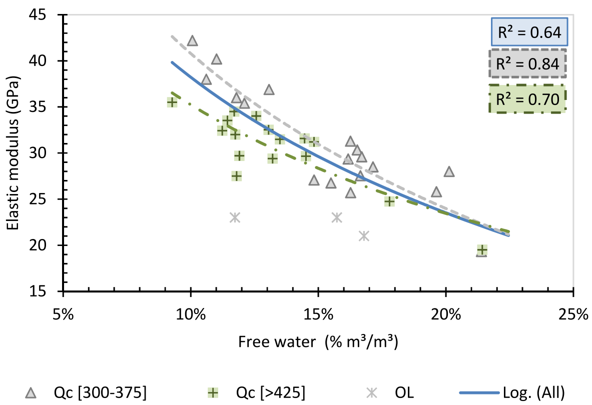


Fig. 4. –Free Water vs Elastic Modulus 55 BRA results. 3 OLs from Ref. [55].

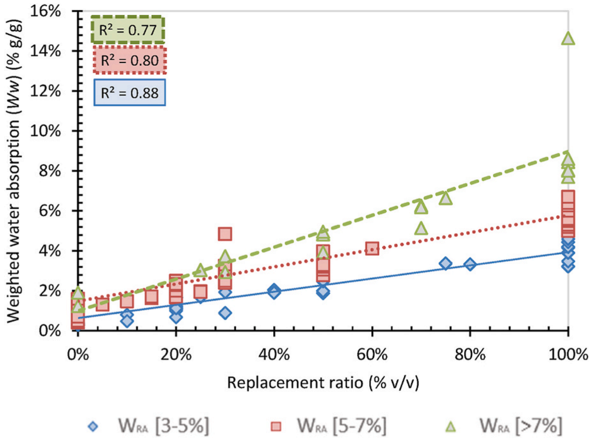


Fig. 5. Weighted water absorption of aggregates (W_W) vs. Replacement Ratio vs. Water absorption from recycled concrete aggregates (W_{RA}). 296 results (122 BRA, 174 *INT*) W_{RA} [3–15 %]).

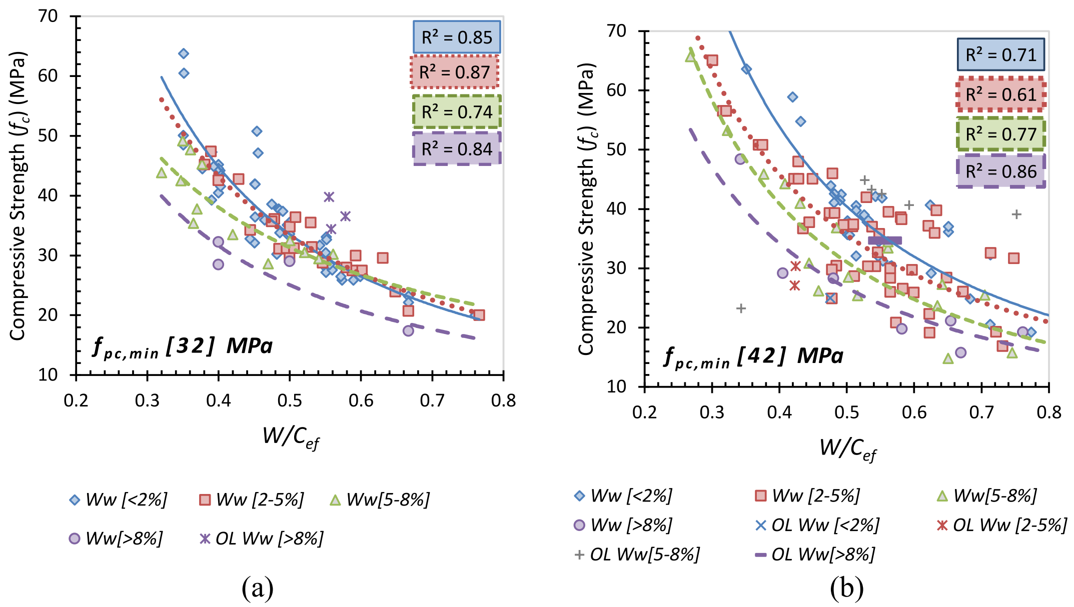


Fig. 6. f_c vs. W/C_{ef} vs. Weighted water absorption (*Ww*) vs cement strength class ($f_{pc,min}$). For (a) $f_{pc,min}$ *32 MPa*; 92 results (60 BRA, 18 *INT*] 3 OLs from Ref. [34]. (b) $f_{pc,min}$ *42 MPa*; 118 results (65 BRA; 53 *INT*) 10 OLs from Refs. [49,53,55,56,66,80,85]).

and those with very low replacement ratios of *RCA*.

By increasing the W_W of the aggregates (different trend lines) as well as increasing the W/C_{ef} ratio, the concrete compressive strength decreases. Therefore, both factors; porosity of the cement paste, and porosity of aggregates needs to be considered. The use of superior minimum-strength class cement ($f_{pc,min}$ *42 MPa*) improves the concrete strength f_c for the same *Ww* and W/C_{ef}. The concrete strength is more affected by the W/C_{ef} than the water absorption of the aggregates, or the cement minimum strength.

The model presented provides better correlations than the prediction model based on the traditional replacement ratio model, for a fixed water to cement ratio, where no effect of the aggregate replacement ratio can be observed on the compressive strength (f_c) without *RCA* subcategorization (see Appendix B, Fig. B1).

The impact of *Ww* on the concrete compressive strength (f_c) depends on W/C_{ef}. For compressive strength (f_c) below 25 MPa (W/C_{ef} > 0.65), the reduction of compressive strength (f_c) in absolute value could be approximately 5 MPa, indicating a greater potential for the use of recycled aggregates, even for the highest *Ww* range (Table 3). For concretes with cement strength class fpc,min *32 MPa* and *W/Cef* [>0.50], there is no difference when using *RCA* with up to *Ww* higher than 8 %. In this case, the strength of concrete is mostly affected by the cement paste porosity, despite the presence of a large variation in the porosity of *RCA*.

For compressive strength (f_c) above 25 MPa, the impact of *Ww* is significant and can exceed 10 MPa. In these cases, the paste porosity was lower, and the porosity of the RCA affected the concrete strength more significantly.

Table 3
Compressive strength reduction, in function of *Weighted water absorption (Ww)*, W/C_{ef} and cement compressive strength ($f_{pc,min}$).

Range of analysis	$f_{pc,min}$ [32]	W/C_{ef}								
		0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75
f_{cmax} (MPa)		**53.5**	**45.0**	**38.6**	**33.6**	**29.8**	**26.9**	24.9	23.4	22.0
Ww [<2 %]	f_{ci}/f_{cmax}	100 %	100 %	100 %	100 %	100 %	99 %	96 %	93 %	90 %
Ww [2–5%]		94 %	96 %	97 %	99 %	100 %	100 %	98 %	96 %	94 %
Ww [5–8%]		80 %	85 %	89 %	93 %	97 %	99 %	100 %	100 %	100 %
Ww [>8 %]		68 %	71 %	73 %	75 %	76 %	77 %	76 %	75 %	75 %
Ww [<2 %]	f_{cmax} - f_{ci}	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.4**	**1.0**	**1.7**	**2.2**
Ww [2–5%]		**3.2**	**1.9**	**1.0**	**0.4**	**0.0**	**0.0**	**0.4**	**0.9**	**1.2**
Ww [5–8%]		10.8	6.9	**4.2**	**2.3**	**1.0**	**0.2**	**0.0**	**0.0**	**0.0**
Ww [>8 %]		17.0	13.2	10.5	8.5	7.1	6.2	**5.9**	**5.7**	**5.6**
Range of analysis	$f_{pc,min}$ [42]	W/C_{ef}								
		0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75
f_{cmax} *(MPa)*		**64.1**	**54.0**	**46.4**	**40.5**	**35.8**	**32.0**	**28.8**	**26.2**	24.0
Ww [<2 %]	f_{ci}/f_{cmax}	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %
Ww [2–5%]		83 %	85 %	86 %	88 %	89 %	90 %	92 %	93 %	94 %
Ww [5–8%]		77 %	78 %	78 %	78 %	79 %	79 %	79 %	80 %	80 %
Ww [>8 %]		62 %	63 %	65 %	66 %	67 %	68 %	69 %	70 %	71 %
Ww [<2 %]	f_{cmax} - f_{ci}	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Ww [2–5%]		10.9	8.2	6.3	**4.9**	**3.9**	**3.1**	**2.4**	**1.9**	**1.5**
Ww [5–8%]		14.7	12.1	10.2	8.7	7.6	6.7	**5.9**	**5.3**	**4.8**
Ww [>8 %]		24.5	19.8	16.4	13.8	11.8	10.2	8.9	7.9	7.0

For structural concrete, the 20 % limit of the replacement ratio of many standard codes for structural recycled concretes can be exceeded by using Ww < 5 % for structural concrete [40–60 MPa], or *Ww* < 8 % [25–40 MPa].

Finally, Brazilian studies present a significant quantity of data in a wider *Ww* range and at a lower cement strength class than those of international studies, allowing for a broader analysis (see Supplementary Table database).

Table 3 shows the relative and absolute reductions in the compressive strength as a function of *Ww*, W/C_{ef}, and cement strength class ($f_{pc,min}$). For comparison, the reduction was calculated as a function of f_{cmax} (maximum value obtained from the regression trend lines in Fig. 6) and f_{ci} (value obtained for each trend line). The bold cells are structural concretes f_c [>25 MPa] or the region where the impact of *Ww* is less significant (<6 MPa). Appendix C presents a guideline of how to explore this model.

4. Conclusions

In this paper a simple way to model the mechanical behavior of concretes with recycled concrete aggregates was proposed. Brazilian data (most of them not published in English) was systematized and provided as a supplementary data file. The elastic modulus and compressive strength of the recycled concretes were modelled based on the porosity law using the criterion of weighted water absorption (*Ww*) of the aggregates and effective water-to-cement ratio (W/C_{ef}). This approach is practical to formulate and manufacture concretes in ready-mix plants with relatively good accuracy and able to optimize fixed rules of %-replacement of natural aggregates by recycled ones. A guideline to explore this model is provided in appendix C.

The 20 % limit of the replacement ratio of many standard codes for structural recycled concretes can be exceeded by using Ww < 5 % for structural concrete [40–60 MPa], or *Ww* < 8 % [25–40 MPa]. Aggregates with *Ww* > 8 % can be used for non-structural concrete applications, with little reduction in compressive strength in absolute terms (<5 MPa). The best %-replacement can be defined for each case, practical for concrete formulations in ready-mix companies.

5. Future outlook

The authors encourage researchers to use the available database to generate additional analysis or to employ in new predictive models based on big data, artificial intelligence, Bayesian statistics (probabilistic approach).

The weighted water absorption of aggregates (*Ww*) could be applied to model the properties of mixed recycled aggregates (with a high content of red ceramic) as well as a trial to include fine recycled aggregates if accuracy errors in water absorption test can be known and controlled.

Parameters like (chemically bound) combined water for each type of cement can improve the Free Water Index (*FW*) calculation and the existing correlations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

excel file added as supplementary material

Acknowledgments

This work was supported by the National Institute of Science and Technology "Advanced Eco-Efficient Cement-Based Technologies", between USP and CNPq and FAPESP agencies (FAPESP process 2014/50948-3). L. Machado thanks the M Sc scholarship provided by Coordination for the Improvement of Higher Education Personnel in Brazil (CAPES) (process: 88887.506272/2020-00). S. C. Angulo thanks research productivity scholarship from CNPq (process 307.458/2021-0), and the Print CAPES internationalization scholarship (process 88887.837891/2023-00).

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2023.108213.

Appendix A. Collected data and List of abbreviations

Table A.1
–Collected Data

ID A	Sector	Data	*Symbol*	ID A	Sector	Data	*Symbol*
A1	Study Information	Author		A30	Materials Characteristics	Water absorption (%)	W_{NA}
A2		Year		A31	-Coarse Natural Aggregates	Density(kg/m^3)	D_{NA}
A3		Institute		A32		Minimum Dimension (mm)	$Dmin_{NA}$
A4		Type of Document		A33		Maximum Dimension (mm)	$Dmax_{NA}$
A5		Country		A34		Fine Modulus	MF_{NA}
A6		Mix ID		A35		Source	
A7	Mix proportioning	Quantity of water (kg/m^3)	Q_W	A36	Materials Characteristics	Water absorption (%)	W_{RA}
A8		Quantity of cement (kg/m^3)	Q_C	A37	-Coarse Recycled Aggregates	Density(kg/m^3)	$D_{A\ RA}$
A9		Quantity of Fine Natural aggregates(kg/m^3)	Q_{FA}	A38		Minimum Dimension (mm)	$Dmin_{RA}$
A10		Quantity of natural aggregates (coarse) (kg/m^3)	$Q\ NA$	A39		Maximum Dimension (mm)	$Dmax_{RA}$
A11		Quantity of recycled aggregates (coarse) (kg/m^3)	Q_{RCA}	A40		Fine Modulus	MF_{RA}
A12		Replacement Ratio (%)	R	A41		Source	
A13		Quantity of additive (kg/m^3)	Q_{AD}	A42		Humidity (%)	
A14		Quantity of SCM (kg/m^3)		A43		Compositions	
A15		Mix proportioning Method		A44		Fines content	
A16	Materials Characteristics –	Type of cement		A45	Concrete Characteristics	*slump* (mm)	
A17	Cement, SCM and additive	Density of Cement (kg/m^3)	D_C	A46		Elastic Modulus (GPa)	E
A18		Cement Specific Superficial Area	SS	A47		Average Compressive Strength (MPa)	f_c
A19		Cement strength Class	fpc,min	A48		Concrete Specimen Size and Geometry	
A20		Cement Strength Test		A49		Water absorption (%)	W_{CO}
A21		Type of additive		A50		Density at Hardened State (kg/m^3)	D_{CO}
A22		Type of SCM		A51		Void Index (%)	VI
A23		Reactive Fraction of cement	RF				
A24	Materials Characteristics	Water absorption (%)	W_{FA}				
A25	-Fine Aggregates	Density(kg/m^3)	D_{FA}				
A26		Minimum Dimension (mm)	$Dmin_{FA}$				
A27		Maximum dimension (mm)	$Dmax_{FA}$				
A28		Fine Modulus	MF_{FA}				
A29		Source					

Table A.2
Average values used to complete missing data.

Aggregate	Origin	Absorption	Density
Fine *NA*	Natural, quartz	0.74 %	2.58 g/cm^3
Coarse *NA*	Basalt	0,22 %	2.80 g/cm^3
	Limestone	0.38 % [106–108]	Completed data*
	Granite	0.7 %	2.6 g/cm^3
	Uninformed	0.7 %	2.72 g/cm^3

* Complete data means that all data were available and were not necessary adopt values outside from study.

Appendix B. Complementary graphs

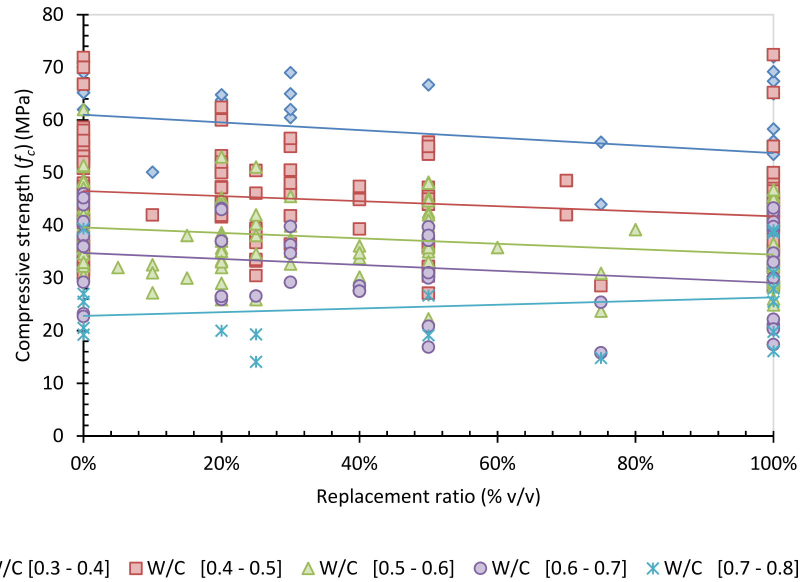


Fig. B.1. Replacement Ratio (R) vs. f_c without *RCA* subcategorization. 138 *BRA* and 212 *INT results*.

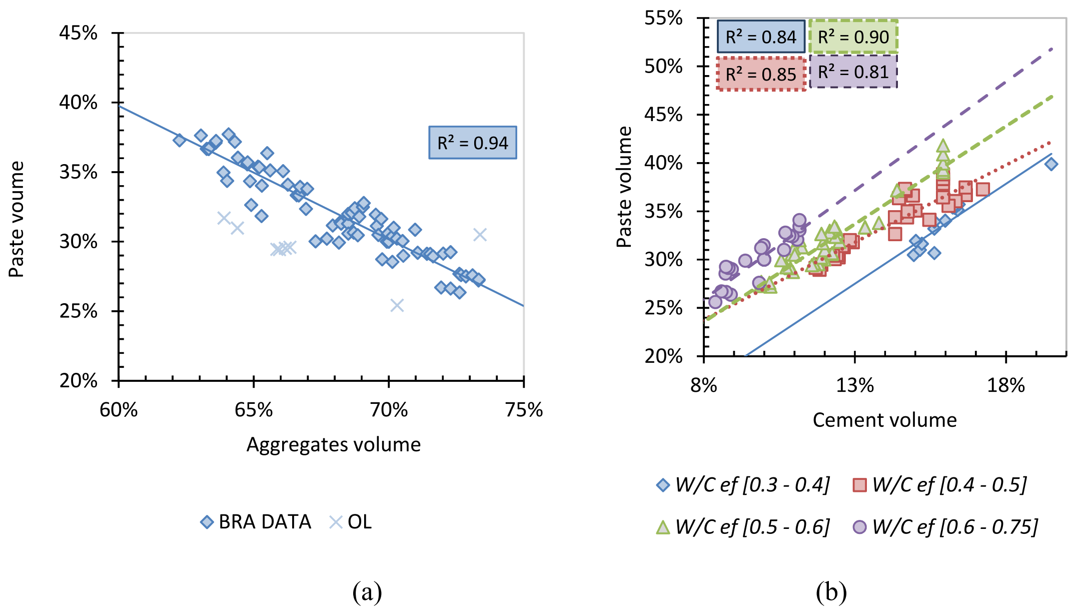


Fig. B.2. a) Aggregates Volume vs. Paste Volume. 104 *BRA* results. 8 OLs (b) Paste Volume vs. Cement Volume for different W/C_{ef}. *BRA* 120 results.

Appendix C. Exploring use of the model

Assumptions

The water absorption of the natural aggregates is less variable than that of the recycled aggregates (Fig. C1a). The aggregates could absorb (or increase) part of water from the fresh concrete, impacting on the W/C_{ef} (Fig. C1b.). The impact depends on the saturation degree, the aggregates water absorption, and the quantity of aggregates.

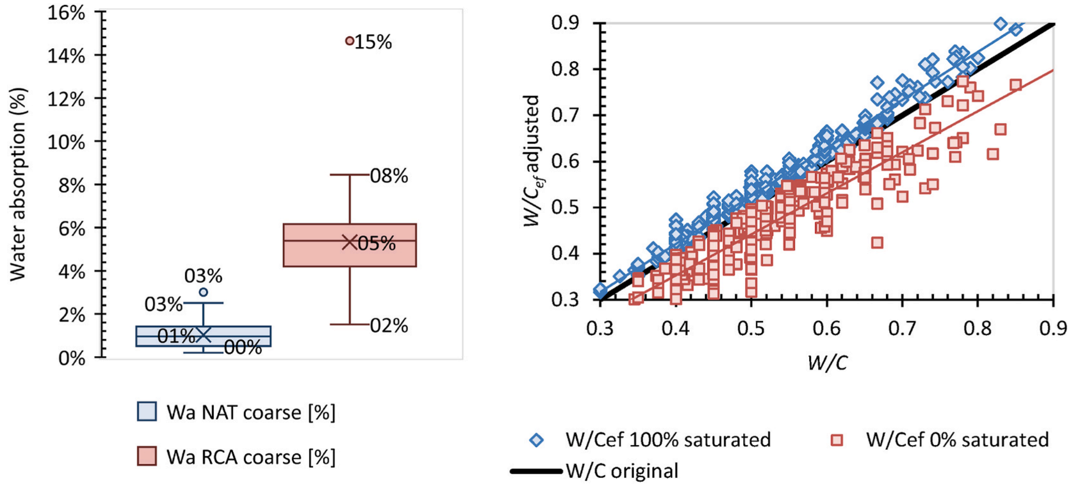


Fig. C.1. (a) Water absorption variation (15 BRA and 25 INT data for NA; 22 BRA and 25 INT data for RA); (b) Variation of W/C_{ef} depending on the saturation degree and water absorption of aggregates (142 BRA; 200 INT data).

From literature, we know that the humidity inside the aggregates affects substantially the fresh properties of the recycled aggregate concrete [99]. Hence, **the humidity of aggregates needs to be determined prior to concrete production.** This is crucial in determining the amount of water needed for pre-wetting or water compensation to produce the recycled aggregate concrete.

The use of an average water absorption value for the recycled aggregates may lead to unacceptable errors when utilizing the predictive model. **The water absorption determination of the recycled concrete aggregate is mandatory prior to concrete production**.

How to use the model.

Table C.1 summarizes the regressions equations of mechanical properties of the recycled aggregate concrete in function of the effective water-to-cement ratio (W/C_{ef}) and the weighted water absorption of the aggregates (W_w). Following the steps proposed in Fig C2, an optimized %-replacement ration for the recycled aggregate concrete is obtained.

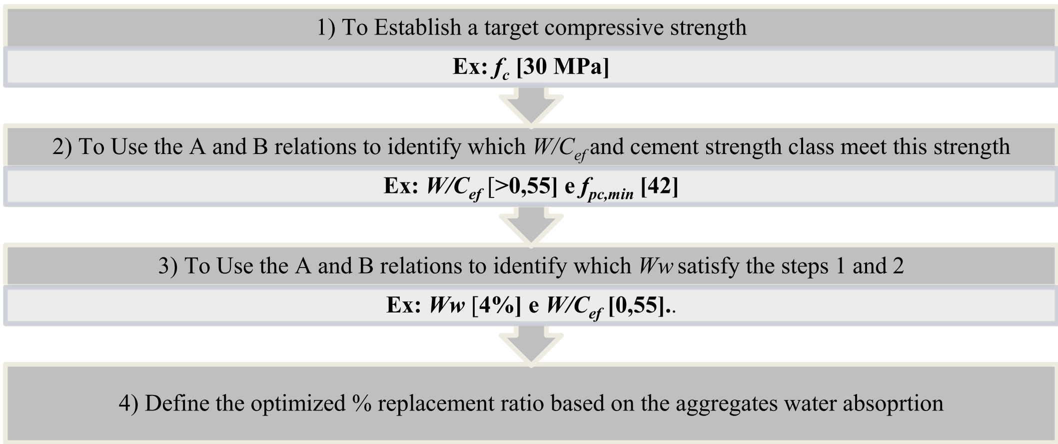


Fig. C.2. Guideline steps.

Accuracy

Two concrete mixtures were used by the authors to check the difference of strength obtained between the predicted by the model and the experimental one (Table C2). The absolute strength difference was 6 MPa, and the strength predicted corresponded to 0.8 of the experimental one.

Pepe [23] proposed a model based on the Compressive Packing Model and compared it with own experiments. Using his mix proportioning (Table C3) but adjusting the saturation condition of the recycled aggregate concrete for 70 % (not as 100 % as suggested by Pepe) to calculate the effective water-to-cement ratio, our model presented a lower accuracy when compared to CPM/Pepe prediction method but with acceptable accuracy (~70–85 % of the experimental one) considering the simplicity of the method. CPM needs more experimental tests as the control of the cement strength and the calibration of some parameters.

Table C.1
Summary of Mechanical properties regressions. Bold cells are structural concretes.

Relation A	Range of analysis	Equation	W/C_{ef}									
			0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0,8
$f_{pc,min}$ [32]– Fig. 7a	*Ww* [<2 %]	$f_c = 13.66{*}W/C_{ef}^{-1.3}$	**53.5**	**45.0**	**38.6**	**33.6**	**29.7**	**26.5**	23.9	21.7	19.9	18.3
f_c = f(W/C_{ef} x *Ww*)	*Ww* [2–5%]	$f_c = 14.89{*}W/C_{ef}^{-1.16}$	**50.3**	**43.1**	**37.6**	**33.3**	**29.8**	**26.9**	24.5	22.5	20.8	19.3
	Ww [5–8%]	$f_c = 17.14{*}W/C_{ef}^{-0.87}$	**42.7**	**38.0**	**34.3**	**31.3**	28.8	26.7	24.9	23.4	22.0	20.8
	Ww [>8 %]	$f_c = 12.13{*}W/C_{ef}^{-1.05}$	**36.5**	**31.7**	**28.1**	**25.1**	22.7	20.7	19.1	17.6	16.4	15.3

Relation B	Range of analysis	Equation	W/C_{ef}									
			0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8
$f_{pc,min}$[42] – Fig. 7b	*Ww* [<2 %]	$f_c = 16.55{*}W/C_{ef}^{-1.29}$	**64.1**	**54.0**	**46.4**	**40.5**	**35.8**	**32.0**	**28.8**	26.2	24.0	22.1
f_c = f(W/C_{ef} x *Ww*) –	*Ww* [2–5%]	$f_c = 16.24{*}W/C_{ef}^{-1.13}$	**53.2**	**45.7**	**40.0**	**35.5**	**31.9**	**28.9**	**26.4**	24.3	22.5	20.9
	Ww [5–8%]	$f_c = 13.17{*}W/C_{ef}^{-1.24}$	**49.4**	**41.8**	**36.1**	**31.7**	**28.2**	**25.3**	22.9	20.9	19.2	17.7
	Ww [>8 %]	$f_c = 12.34{*}W/C_{ef}^{-1.11}$	**39.6**	**34.1**	**29.9**	**26.6**	24.0	21.8	19.9	18.3	17.0	15.8

Relation C	Equation	Free water (%)									
		9,5 %	10.8 %	12.1 %	13.4 %	14.7 %	16.0 %	17.3 %	18.6 %	19.9 %	21.2 %
E = f(FW) – Fig. 6	$E = 62.21\ exp^{(-5.03FW)}$	38.6	36.1	33.8	31.7	29.7	27.8	26.1	24.4	22.9	21.4

Table C.2
Experimental concrete mix proportioning. Further details can be found in Ref. [109].

Quantity of materials (kg/m^3)	*Mix I*	*Mix II*
Cement	330	324
Natural sand	325	319
Crushed rock sand	480	471
Natural coarse aggregate	997	0
Recycled coarse concrete aggregate	0	838
Total water	219	243
[1]Pre-wetting water *NA*	5	0
[1]Pre-wetting water *RCA*	0	32
% poli functional admixture	0.8%m.c	0,8%m.c
W/C_{ef}	0.65	0.65
Slump (mm)	100	100
f_c average (Mpa)	35.0	32.9
Standard deviation (Mpa) (20 specimens)	1.0	1.1
F_c *predicted* (MPa) - (Relation B - Table D1)	28.8	26.4
Absolute difference -[f_c predicted - f_c measured] (MPa)	6.2	6.5
Relative difference - [(f_c predicted/f_c measured)] (%)	82 %	80 %

Table C.3
Concrete mix proportioning done by Pepe [23].

ID	Cement (kg/m^3)	Water (kg/m^3)	W/C	*RCA* 1 (kg/m^3)	*RCA* 2 (kg/m^3)	*NA* (kg/m^3)	*WA RCA* 1	*WA RCA* 2	*WA NA*
RAC45	316	127	0.40	0	1026	162	11.9 %	4.9 %	1.28 %
RAC37	300	137	0.46	358	417	0	11.9 %	4.9 %	1.28 %

Table C.4
Comparison between prediction strength models

ID	*Ww*	*WC*	Predictive equation of our model (see table D1)	R^2	f_c estimated Our model (MPa)	f_c estimated CPM (MPa)	f_c Experimental results (MPa)	Relative difference (our model)	Relative difference (CPM)
RAC45	4.4 %	4.4 %	$f_c = 16,24 \times W/C_{ef}^{-1,13}$	0.72	40.0	44.9	46.4	86 %	97 %
RAC37	8.2 %	8.2 %	$f_c = 12,34 \times W/C_{ef}^{-1,11}$	0.88	25.5	37.1	36.3	70 %	102 %

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List of abbreviations

BRA –: Brazilian database
CDW –: Construction and Demolition Wastes

E –Elastic Modulus

f_c *–:* Average Compressive Strength
fpc,min –: Cement strength class
FW –: Free Water
INT –: International database
ITZ –: Interfacial transition zone
MPT –: Maximum Paste Thickness
NA –: Natural Aggregate
Q_C *-:* Quantity of Cement (kg/m^3 of concrete)
Q_{FA} *–:* Quantity of fine aggregate (kg/m^3 of concrete)

Q_{NA} -: Quantity of NA (kg/m^3 of concrete)
Q_{RCA} -: Quantity of RCA (kg/m^3 of concrete)
Q_W -: Quantity of Water (kg/m^3 of concrete)
R –: Replacement Ratio
RA –: Recycled Aggregate
RAC –: Recycled Aggregate Concrete
RCA –: Recycled Concrete Aggregate
W_{NA}: Water absorption of NA
W_{RA}: Water absorption of RA
W_W –: Water absorption - weighted
W/C -: Water Cement Ratio
W/C_{ef} –: Effective Water Cement Ratio