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New formulations for mechanical properties of recycled aggregate concrete using gene expression programming

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HIGHLIGHTS

- New models are developed by GEP technique to predict mechanical properties of recycled aggregate concrete (RAC).
- A comprehensive database covering a wide range of parameters is assembled through an extensive review of the literature.
- w_{eff}/c and $RCA\%$ are the most influential parameters on mechanical properties of RAC.
- Simple and accurate formulations with a wide range of applicability have been proposed.
- Predictions of the proposed models are consistent with those of the currently used code expressions for natural aggregate concrete.

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ABSTRACT

This paper presents new empirical models for prediction of the mechanical properties of recycled aggregate concrete (RAC) using gene expression programming (GEP) technique. A large and reliable test database containing the results of 650 compressive strength, 421 elastic modulus, 346 splitting tensile strength, and 152 flexural strength, tests of RACs containing no pozzolanic admixtures is collated through an extensive review of the literature. The performance of existing mechanical property models of RACs is then assessed using the database, and the results of this assessment are presented using selected statistical indicators. New expressions for the predictions of 28-day compressive strength, elastic modulus, flexural strength, and splitting tensile strength of RACs are developed based on the database. The assessment results indicate that the predictions of the proposed models are in close agreement with the test results, and the new models provide improved estimates of the mechanical properties of RACs compared to the existing models.

1. Introduction

Rapid industrial and population growths have resulted in the increased rate of demolition of old structures in order to obtain new construction sites. Generation and disposal of the huge amount of construction and demolition waste in the landfills caused environmental problems by depleting the landfill areas [1–3]. Over the past two decades, the use of recycled concrete aggregate, obtained from construction and demolition waste, as an alternative to non-renewable natural aggregate in concrete has been considered to improve resource sustainability in the construction industry and minimize the environmental impact of the disposed construction and demolition waste [4–6]. The use of recycled concrete as coarse aggregates in the new concrete mix is recognized as an attractive technology to conserve natural resources and reduce the environmental impact of the construction industry [2,3,7–9]. However, as a result of the variability in the characteristics of the recycled concrete aggregates, the mechanical properties of RACs obtained using them vary from those of natural aggregate concrete (NAC). Therefore, understanding the relationship between the mechanical properties and mix proportions of RAC is essential before the material can widely be adopted by the construction industry.

The compressive strength, elastic modulus, flexural strength, and splitting tensile strength are the key material properties for the analysis and design of concrete structures. A comprehensive review of the existing studies on RAC has shown that a number of models have been reported in the literature to predict these mechanical properties for RAC [10–30]. However, because of the limitations in the parametric ranges of the considered experimental results as well as the relatively small test databases used in the

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calibration of the models, the existing models are often restricted to specific specimen subsets and they might not provide accurate predictions of the mechanical properties of RAC beyond these parametric spaces. Therefore, a large and carefully constructed database, covering a wide range of parameters, is needed to develop reliable and accurate expressions to predict the mechanical properties of RAC. Such a database is presented in the current paper.

Recent technological progress in artificial intelligence techniques has generated accurate and reliable computer-aided modeling procedures for structural engineering problems [31–39]. Application of machine learning and computational intelligence methods to predict the mechanical properties of RAC has also received recent research attention. Younis and Pilakoutas [9] proposed a strength model to predict the compressive strength of the RAC using multi-linear and non-linear regressing analysis. Duan et al. [40] and Sahoo et al. [41] utilized artificial neural networks (ANN) method to predict the compressive strength of the RAC. Deshpande et al. [42] modeled the compressive strength of the RAC by ANN, model tree, and nonlinear regression methods. Duan et al. [43] utilized ANN method to predict the elastic modulus of RAC. Behnood et al. [44] predicted elastic modulus of RAC using M5 model tree algorithm. Recently, Gonzalez-Taboada et al. [45] proposed models to predict the compressive strength, elastic modulus, and splitting tensile strength of RAC using multivariable regression and genetic programming.

Pattern recognition of the computational intelligence methods plays a significant role in the application of them in the engineering applications. Most of the existing computational intelligence methods (e.g. ANN and support vector regression) are capable of providing complex pattern recognition through black-box models. However, the structure of these methods needs to be predefined by a base form, which requires extensive memory size [46,47]. Genetic Programming (GP) is a powerful optimization technique based on the genetic and natural selections. The main advantage of the GP-based methods is their ability to provide simple expressions without the need to assume a base form. GP provides a relatively new pattern recognition procedure for civil engineering applications [47,48]. Gene expression programming (GEP) introduced by Ferreira [49] is an extended GP-based method. In GEP, linear chromosomes as several genes with a fixed length encode a smaller program. Recent studies indicated that GEP can be an efficient alternative to the traditional GP method in civil engineering applications [46–51]. In these studies, GEP has been used for prediction of compressive strength of foam concrete, compressive strength of steel fiber reinforced concrete under triaxial compression, moment capacity of ferrocement members, shear strength of reinforced concrete deep beams, flow number of asphalt mixture, and liquefaction potential of soil. However, the use of GEP in structural engineering applications has remained limited, and no study to date has considered its application to predict the mechanical properties of RAC.

In this study, empirical models are proposed using GEP technique to predict 28-day compressive strength, elastic modulus, flexural strength, and splitting tensile strength of RAC. In addition, 34 existing mechanical properties models of RAC collected from 21 published studies are reviewed and assessed through statistical analysis using a reliable and comprehensive database containing samples with a wide range of mixture proportions.

2. Experimental database

The RAC database in Table A1 in the Appendix was compiled from 69 experimental studies in the literature. The results included in the database were obtained from concrete specimens manufactured using mixes that contained no pozzolanic admixtures. The resulting database consists of 332 compressive strength results obtained from cube specimens ($f'_{c,cube}$), 318 compressive strength results obtained from cylinder specimens ($f'_{c,cylinder}$), 421 elastic modulus (E_c) results, 152 flexural strength (f_r) results, and 346 splitting tensile strength (f_{st}) results.

The database shown in Table A1 contains information for each dataset including the type and size of the specimens, the effective water-to-cement binder ratio (w_{eff}/c), aggregate-to-cement ratio (a/c), maximum particle size (Φ) of recycled concrete aggregates and natural aggregates, air-dried density (ρ_{ad}) and saturated surface dry density of hardened concrete (ρ_{ssd}), strength of the parent concrete recycled concrete aggregate derived from ($f'_{c,p}$), recycled concrete aggregate replacement ratio ($RCA\%$), water absorption of recycled concrete aggregates and natural aggregates (WA_{RCA} and WA_{NA}, respectively), bulk density of coarse recycled concrete aggregates and natural aggregates (ρ_{RCA} and ρ_{NA}, respectively), Los Angeles abrasion index of recycled concrete aggregates and natural aggregates (LA_{RCA} and LA_{NA}, respectively), compressive strength of concrete (f'_c), elastic modulus of concrete (E_c), flexural strength of concrete (f_r), and splitting tensile strength of concrete (f_{st}). The distribution of the most influential parameters (i.e. w_{eff}/c and $RCA\%$) are shown in Fig. 1 for the specimens in the database.

Three types of specimens were used in obtaining the mechanical properties in Table A1; namely, cylinders, cubes, and beams. For each type of specimen, two different sizes were used in the tests, which are indicated by the labels. The cylinders had a diameter of either 100 or 150 mm and a height-to-diameter ratio of two, which are labeled as C_1 and C_2, respectively; cubes had a dimension of 100 or 150 mm, which are labeled as S_1 and S_2, respectively; and beams had a dimension of $100 \times 100 \times 500$ mm or $150 \times 150 \times 750$ mm, which are labeled as B_1 and B_2, respectively. In Table A1, w_{eff}/c of the specimens varied from 0.19 to 0.87, $RCA\%$

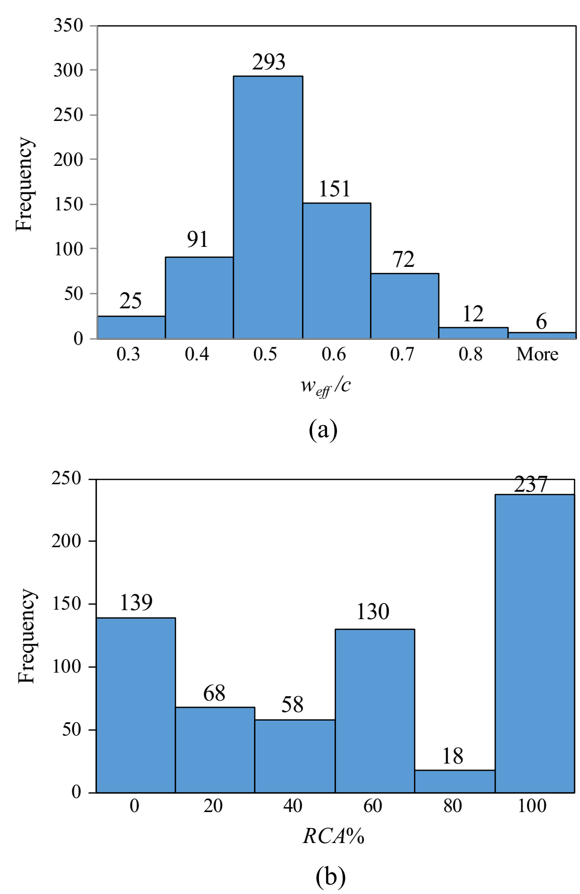

Fig. 1. Distribution histograms of: (a) w_{eff}/c; (b) $RCA\%$.

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Table 1
Summary of existing models to predict mechanical properties of RAC.

Year	Model	Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f_r) (MPa)	Splitting tensile strength (f_{st}) (MPa)
1985	Ravindrarajah and Tam [16]		$7770f'^{0.33}_{c,cube}$		
1988	Kakizaki et al. [15]		$1.9 \cdot 10^5 \cdot (\frac{\rho_h}{2400})^{1.5} \cdot \sqrt{\frac{f'_{c,cube}}{2000}}$		
1993	Bairagi et al. [17]		$(5780 - 1340 \cdot RCA\%)\sqrt{f'_{c,cube}}$	$(0.82 - 0.16 \cdot RCA\%)\sqrt{f'_{c,cube}}$	
1996	de Oliveira and Vazquez [18]		$2.15 \cdot 10^4 \sqrt[3]{0.1f'_{c,cube}}$		
1996	Tavakoli and Soroushian [21]		$378f'_{c,cube} + 8242$	$0.62\sqrt{f'_{c,cube}}$ (ACI 318)	$0.5\sqrt{f'_{c,cube}}$
1998	Dillmann [19]		$634.43f'_{c,cube} + 3057.6$		
1999	Dhir [20]		$370f'_{c,cube} + 13100$		
2001	Zilch and Roos [22]		$9100(f'_{c,cylinder} + 8)^{1/3} \cdot (\frac{\rho_h}{2400})^2$		
2005	Kheder and Al-Windawi [23]		$4993f'^{0.422}_{c,cylinder}$	$0.762f'^{0.473}_{c,cylinder}$	$0.568f'^{0.499}_{c,cylinder}$
2006	Xiao et al. [10]	$f'_{c,cube} = 0.069\rho_h - 116.1$	$\frac{10^5}{2.8+\frac{40.1}{f'_{c,cube}}}$	$0.75\sqrt{f'_{c,cube}}$	$0.24\sqrt{f'^{0.65}_{c,cube}}$
2006	Xiao et al. [29]				$(0.24 - 0.06 \cdot RCA\%)f'^{2/3}_{c,cube}$
2007	Rahal [24]		$\rho_h^{1.5} \cdot 0.043\sqrt{f'_{c,cylinder}}$		
2010	Corinaldesi [25]		$18,800 \cdot \sqrt[3]{0.083 \cdot f'_{c,ylinder}}$		
2012	Sriravindrarajah et al. [11]	$f'_{c,cube} = 22.2e^{-0.052P}$$P$ is the porosity of the concrete			
2012	Lovato et al. [12]	$f'_{c,cylinder} = 22.5(\frac{0.5}{w_{eff}/c})^{0.67} \cdot (1 - \frac{RCA\%}{7.44}) \cdot FRA\% \cdot (1 - \frac{a/c}{8.61}) \cdot$ $[1 - (-0.04 \cdot RCA\% \cdot a/c)] \cdot [1 - (0.008 \cdot FRA\% \cdot a/c)]$where *FRA%* is fine recycled aggregate percentage	$13.49(\frac{0.5}{w_{eff}/c})^{0.48} \cdot (1 - \frac{RCA\%}{5.76}) \cdot (1 - \frac{FRA\%}{5.49}) \cdot (1 - \frac{a/c}{8.67}) \cdot$ $[1 - (-0.04 \cdot RCA\% \cdot a/c)]10^3$		$1.86(1 - \frac{RCA\%}{6.81}) \cdot (1 - \frac{FRA\%}{9.86}) \cdot$ $(1 - \frac{a/c}{4.87}) \cdot [1 - (-0.016 \cdot$ $RCA\% \cdot a/c)]$
2012	Hoffmann et al. [26]		$6800\sqrt[3]{f'_{c,ylinder}}$		
2012	Pereira et al. [13]	$f'_{c,cube} = k_1/k_2^{(w_{eff}/c)} \cdot (1 - k_3 \cdot WA_{RCA} \cdot RCA\%)$ k_1 = 230.3, k_2 = 25.9, k_3 = -0.077 where WA_{RCA} is water absorption rate of recycled concrete aggregate			
2012	Pereira et al.[27]		$4.228 \cdot f'^{1/3}_{c,cube}((1 - RCA\%) \cdot \rho_{NA} +$ $RCA\% \cdot \rho_{RcA})[\frac{(0.55)}{(w_{eff}/c)}]^{0.22}$		$0.096 \cdot f'^{2/3}_{c,cube}((1 - RCA\%) \cdot$ $\rho_{NA} + RCA\% \cdot \rho_{RCA})[\frac{0.55}{(w_{eff}/c)}]^{0.177}$
2013	Thomas et al.[14]	$f'_{c,ylinder} = -0.32 + 0.022 \cdot RCA\% + (1 - 0.0025 \cdot RCA\%) \cdot f'_{c-NA}$ $f'_{c\text{-}NA}$ is the compressive strength of the companion NAC			
2013	Younis and Pilakoutas [9]	$f'_{c,cube} = [13.7\frac{\rho_{RCA}}{\rho_{NA}} + 2.47\frac{LA_{RCA}}{LA_{NA}} - 0.2\frac{WA_{RCA}}{WA_{NA}} - 0.12RCA\% - 10.35] \cdot f'_{c-NA}$ $f'_{c,cube} = [-1.245\frac{\rho_{RCA}}{\rho_{NA}} + 3.22\frac{LA_{NA}}{LA_{RCA}} - 0.99\frac{WA_{NA}}{WA_{RCA}} - 0.13RCA\%] \cdot f'_{c-NA}$ $f'_{c,cube} = [f'_{c-NA} \cdot (\frac{\rho_{RCA}}{\rho_{NA}})^{-0.15} \cdot (\frac{LA_{RCA}}{LA_{NA}})^{-3.6} \cdot (\frac{WA_{RCA}}{WA_{NA}})^{0.65}] \div (RCA\% + 1)^{0.12}$ where LA_{RCA} and LA_{NA}, respectively, are the Los Angeles abrasion index for recycled concrete aggregate and NA, and WA_{NA} is water absorption rate of NA			
2014	Wardeh et al. [28]		$E_c = 17553(0.1 \cdot f'_{c,cube})^{0.42}$		

*In this table, f'_c, E_c, f_r, f_{st} and $f'_{c\text{-}NA}$ are in MPa; ρ_h, ρ_{RCA} and ρ_{NA} are in kg/m^3; P, WA_{RCA}, and WA_{NA} are in% .

varied from 0 to 100, f_c varied from 13.4 to 108.5 MPa, E_c varied from 12.5 to 50.4 GPa, f_r varied from 1.9 to 10.2 MPa, and f_{st} varied from 1.1 to 6.3 MPa.

It should be noted that, as marked in Table A1, the datasets that deviated significantly from the global trends of the database (i.e. ±50%) were excluded from the model assessment and were not used in the subsequent model development. This resulted in 508 compressive strength results, 251 from cube specimens and 257 from cylinder specimens; 351 elastic modulus results; 118 flexural strength results; and 307 splitting tensile strength results that were used in the model assessment and development.

3. Existing models for predicting mechanical behavior of RAC

Table 1 presents the existing models, obtained from 21 different studies in the literature, to predict the mechanical properties of RAC. These include the eight models for compressive strength [9–14], 16 models for elastic modulus [10,12,15–28], four models for flexural strength [10,17,21,23], and six models for splitting tensile strength [10,12,21,23,27,29]. All models contain closed-form equations, which were developed by regression analysis of the experimental test results, and hence their accuracy is dependent on the size, reliability, and parametric range of the test databases used in the model development.

4. Gene expression programming

Gene expression programming (GEP) was developed by Ferreira [49] as a branch of genetic programming (GP) and it is based on five different components of: a function set, a terminal set, a fitness function, control parameters, and a terminal condition. A character string with a fixed length is used in the GEP algorithm in order to obtain the solution, whereas GP technique uses a parse tree structure, which can vary in length during the run in the computer program. The creation of the genetic variety in the GEP is extremely simple because of the genetic mechanism of this technique at the chromosome level. Furthermore, because of its multi-genic nature, GEP allows the development of complex and nonlinear programs with several subprograms. In GEP, each gene consists of two types of symbols: a fixed length variables and constants as terminal set (e.g. {a,b,c,6}) and arithmetic operations as function set (e.g. {+,–,×,÷,log}). The key feature of the GEP is the creation of the chromosomes, which are capable of representing any parse tree using Karva language to read and express the information encoded in the chromosomes. The chromosomes are then translated to the branched structures of expression tree (ET). The transformation of the Karva expression (K-expression) to an ET initiates from the first position in the K-expression, as the root of ET, and continues through the string. In order to generate the string, the ET is inversely transformed to the K-expression using the record of the nodes from the root layer to the deepest layer. In the GEP algorithm, because of the predefined and fixed length of the genes and the variability in the corresponding ETs' size, there is a number of extra elements which is not effective in the mapping process of the genome. Therefore, the K-expression's length can be less than or equal to that of the GEP gene [46,48].

Fig. 2 shows the schematic of the GEP algorithm. The algorithm starts with the random creation of the chromosome with the fixed length for each evolving program (individual). Subsequently, the chromosomes are declared, and the fitness of each individual is evaluated. Following this, the individuals are chosen based on their fitness results in order to apply the reproduction. The process is repeated with the new individual for a series of generations until a solution is found. In this approach, conversion in the population is provided by performing genetic operations, such as mutation, rotation, and crossover, on the selected program.

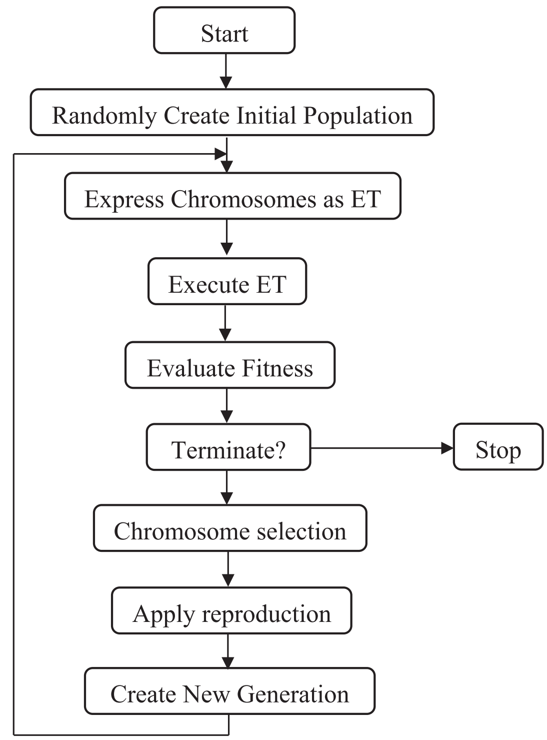

Fig. 2. Schematic presentation of the GEP algorithm.

5. Performance measures

To increase the accuracy of the developed models, the experimental database was randomly separated into three different subsets of learning, validation, and testing. In this division, the learning data were used for the genetic development, the validation data for the final model selection, and the testing data for the determination of the accuracy of the GEP models in regard to the data that do not play any role in the structure of the models. The final models are selected using an objective function (OBJ) based on the best performance of both learning and validation data sets. The objective function, defined as Eq. (1), is minimized to select the best GEP models [47].

$$\mathrm{OBJ} = \left(\frac{n_L - n_V}{n_T}\right)\rho_L + \left(\frac{2n_V}{n_T}\right)\rho_V \tag{1}$$

where n is the number of the data points, ρ is the performance index, and subscripts L, V, and T are learning, validation, and testing data sets, respectively. Four statistical indexes including the average absolute error (AAE), root mean square error (RMSE), mean (M), and covariance (COV) are used to assess the model performance. The definitions of AAE, RMSE, M, COV, and ρ [47] are given in Eqs. (2)–(6).

$$\mathrm{AAE} = \frac{1}{n}\sum_{i=1}^{n}\frac{|t_i - u_i|}{t_i} \times 100 \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(t_i - u_i)^2}{n}} \tag{3}$$

$$\mathrm{M} = \frac{1}{n}\sum_{i=1}^{n}\frac{u_i}{t_i} \tag{4}$$

$$\mathrm{COV} = \frac{1}{\mathrm{M}}\sqrt{\frac{\sum_{i=1}^{n}\left(\frac{u_i}{t_i} - \frac{\overline{u}}{t}\right)^2}{n-1}} \tag{5}$$

$$\rho = \frac{\mathrm{RMSE}/\overline{t}}{1 + \frac{\sum_{i=1}^{n}(u_i - \overline{u}_i)(t_i - \overline{t}_i)}{\sqrt{\sum_{i=1}^{n}(u_i - \overline{u}_i)^2 \sum_{i=1}^{n}(t_i - \overline{t}_i)^2}}} \tag{6}$$

where u_i and t_i are ith predicted and experimental outputs, respectively; $\overline{u}_i$ and $\overline{t}_i$ are ith average values of the predicted and experimental outputs, respectively; and $\overline{t}$ is the average value of the experimental output.

6. Model development using GEP

In order to obtain the relationships between mechanical properties of RAC and the influential parameters with improved accuracy, the specimens in the database were closely studied and the main factors affecting the mechanical properties of RACs were determined. To evaluate the contribution of each input parameter on the mechanical properties, sensitivity analysis (SA) was performed through the determination of frequency values of the input parameters. The percentage of contribution of each input parameter is calculated using Eqs. (7) and (8) [113]:

$$L_i = f_{max}(x_i) - f_{min}(x_i) \tag{7}$$

$$\mathrm{SA}_i = \frac{L_i}{\sum_{j=1}^{n} L_j} \times 100 \tag{8}$$

where $f_{max}(x_i)$ and $f_{min}(x_i)$ are maximum and minimum of the predicted output based on the ith input domain when other input values are constant at the average value. Figs. 3(a)–(d) show the sensitivity analysis of compressive strength, elastic modulus, flexural strength, and splitting tensile strength, respectively. It can be seen in these figures that the most influential parameters on the mechanical properties of RAC are w_{eff}/c and $RCA\%$. Fig. 3 shows that the relative influences of w_{eff}/c and $RCA\%$ remain mostly constant across the mechanical properties investigated in this study.

Consequently, the compressive strength (f'_c), elastic modulus (E_c), flexural strength (f_r), and splitting tensile strength (f_{st}) are considered to be a function of the following parameters:

$$f'_c, E_c, f_r, \text{and} f_{st} = f(w_{eff}/c, RCA\%) \tag{9}$$

Based on Eq. (9), w_{eff}/c and $RCA\%$ were employed to generate the mechanical property models using the GEP algorithm. Several runs were performed to ensure adequate robustness and generalization of the models. The fitting parameters for the GEP algorithm were chosen based on the previously suggested values by Gandomi et al. [50,114] and a number of initial runs. Population size (i.e. number of chromosomes) sets the running time, with a larger size results in a longer time. Based on the number of possible solutions and complexity of the problem, three optimal levels were set for the population size, i.e. 50, 150, and 300. Head size and number of genes, which evolve the chromosome architectures of the models, specify the complexity of each gene and the number of sub-ET in the evolved model, respectively. The increase of the genes number usually results in overfitting and generation of a complex function. Based on the suggestion by Gandomi et al. [48], the head size

Table 2
Optimal parameter settings for GEP algorithm.

Parameter	Settings
General	
Chromosomes	30
Genes	10
Gene size	7
Numerical constant	
Constants per gene	1
Data type	Floating number
Lower bound	−10
Upper bound	10

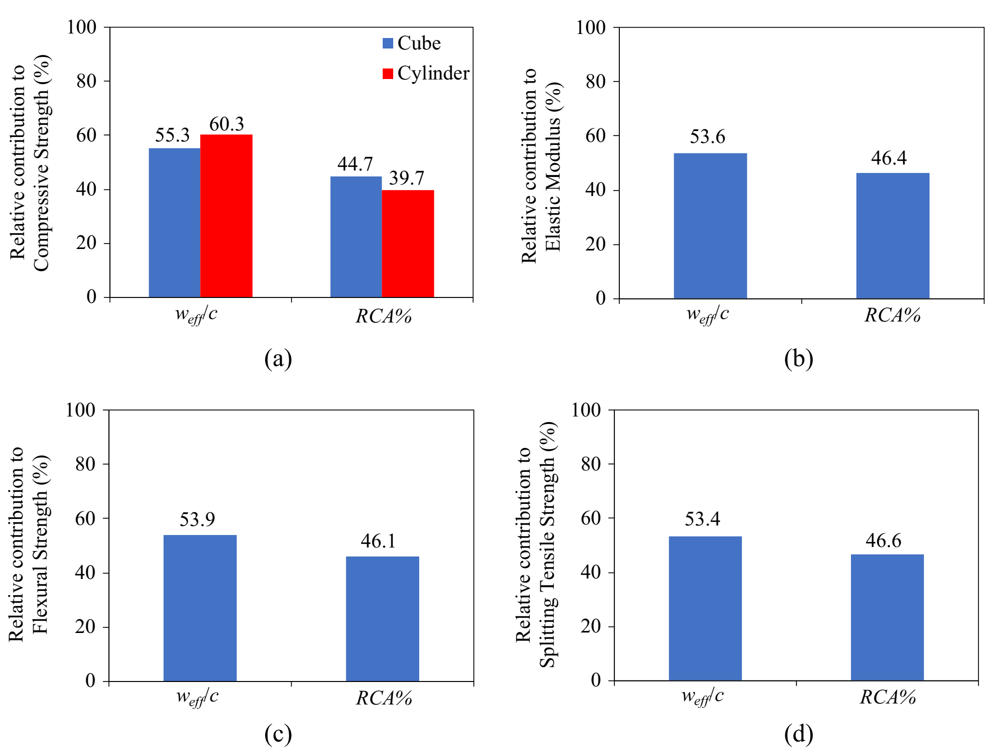

Fig. 3. Sensitivity analysis of: (a) compressive strength, (b) elastic modulus, (c) flexural strength, and (d) splitting tensile strength of RAC.

was set as 1, and the number of genes was set as two in this study. The optimal values of the other parameters in the GEP algorithm are shown in Table 2. These values were obtained from 10 different runs for each combination adopting a trial-and-error method [48,115].

6.1. GEP-based formulation of the compressive strength of RAC

The performance of existing compressive strength models was assessed using the database to evaluate the accuracy and relative performance of the models. Based on the available input parameters in the database, only three compressive strength models, i.e. Xiao et al. [10], Pereira et al. [13], and Thomas et al. [14] models, could be used in the model assessment. Two of these models were given for cube specimens [10,13], and one for cylinder specimens [14]. The other compressive strength models (i.e. Refs. [9], [11], and [12]) required specific input parameters that were not available in the database.

In this study, two compressive strength models were developed; one to predict the cube strength ($f'_{c,cube}$) and one to predict

Table 3
Model predictions of compressive strength (f'_c) of RAC.

Model	Number of datasets	AAE (%)	RMSE (MPa)	Mean	ρ	COV	Specimen type
Xiao et al. [10]	74	12.7	11.3	0.98	0.17	0.19	Cube
Pereira et al. [13]	157	22.2	11.8	1.14	0.15	0.24	Cube
Thomas et al. [14]	257	14.6	8.1	1.09	0.11	0.19	Cylinder
Proposed model	251	12.4	7.9	1.02	0.09	0.17	Cube
Proposed model	257	14.4	7.8	1.01	0.11	0.19	Cylinder

Table 4
Model predictions of elastic modulus (E_c) of RAC.

Model	Number of datasets	AAE (%)	RMSE (GPa)	Mean	ρ	COV
Xiao et al. [10]	104	14.3	6.17	0.91	0.14	0.16
Kakizaki et al. [15]	33	10.9	4.51	0.92	0.08	0.13
Ravindrarajah and Tam [16]	104	13.1	5.62	0.93	0.12	0.16
Bairagi et al. [17]	104	19.1	6.76	1.15	0.13	0.16
de Oliveira and Vazquez [18]	104	22.3	7.14	1.20	0.15	0.16
Dillmann [19]	104	21.7	8.40	1.11	0.17	0.23
Dhir [20]	104	14.3	5.15	1.03	0.11	0.17
Tavakoli and Soroushian [21]	104	16.8	6.55	0.88	0.13	0.19
Pereira et al. [27]	82	31.1	10.54	1.29	0.22	0.17
Wardeh et al. [28]	104	17.2	5.79	1.13	0.12	0.16
Lovato et al. [12]	204	70.6	21.8	0.29	0.53	0.24
Zilch and Roos [22]	84	8.3	3.10	1.06	0.06	0.10
Kheder and Al-Windawi [23]	172	18.7	6.76	0.82	0.14	0.12
Rahal [24]	84	10.1	3.74	1.08	0.07	0.10
Corinaldesi [25]	172	10.1	3.85	0.96	0.08	0.12
Hoffmann et al. [26]	172	21.5	7.65	0.79	0.16	0.12
Proposed model	351	10.1	3.06	1.00	0.06	0.10

Table 5
Model predictions of flexural strength (f_r) of RAC.

Model	Number of datasets	AAE (%)	RMSE (MPa)	Mean	ρ	COV
Xiao et al. [10]	19	8.1	0.52	0.99	0.06	0.09
Bairagi et al. [17]	19	11.1	0.73	0.99	0.08	0.13
Tavakoli and Soroushian [21]	19	17.9	1.12	0.82	0.12	0.09
Kheder and Al-Windawi [23]	54	16.1	0.97	0.95	0.14	0.20
Proposed model	118	8.1	0.52	0.99	0.05	0.08

Table 6
Model predictions of splitting tensile strength (f_{st}) of RAC.

Model	Number of datasets	AAE (%)	RMSE (MPa)	Mean	ρ	COV
Xiao et al. [10]	109	16.6	0.52	0.96	0.10	0.19
Tavakoli and Soroushian [21]	109	20.3	0.57	1.16	0.10	0.22
Pereira et al. [27]	58	17.3	0.78	1.12	0.15	0.24
Xiao et al. [29]	109	16.6	0.67	0.86	0.13	0.18
Lovato et al. [12]	149	76.4	2.50	0.23	0.62	0.43
Kheder and Al-Windawi [23]	139	23.1	0.77	1.20	0.16	0.18
Proposed model	307	15.8	0.51	0.99	0.10	0.17

the cylinder strength ($f'_{c,cylinder}$). The proposed equations are obtained from 10 subprograms (i.e. genes), with each of them investigating an individual aspect of the problem [50]. The following expressions are proposed to predict the strengths at the age of 28 days for RACs with compressive strengths of up to 110 MPa:

$$f'_{c,cube}(\mathrm{MPa}) = \frac{19.1 \times 0.998^{RCA\%} \times (w_{eff}/c + 0.33)}{w_{eff}/c^{1.5}} \tag{10}$$

$$f'_{c,cylinder}(\mathrm{MPa}) = \frac{23.5 \times 0.998^{RCA\%} \times (w_{eff}/c + 0.09)}{w_{eff}/c^{1.7}} \tag{11}$$

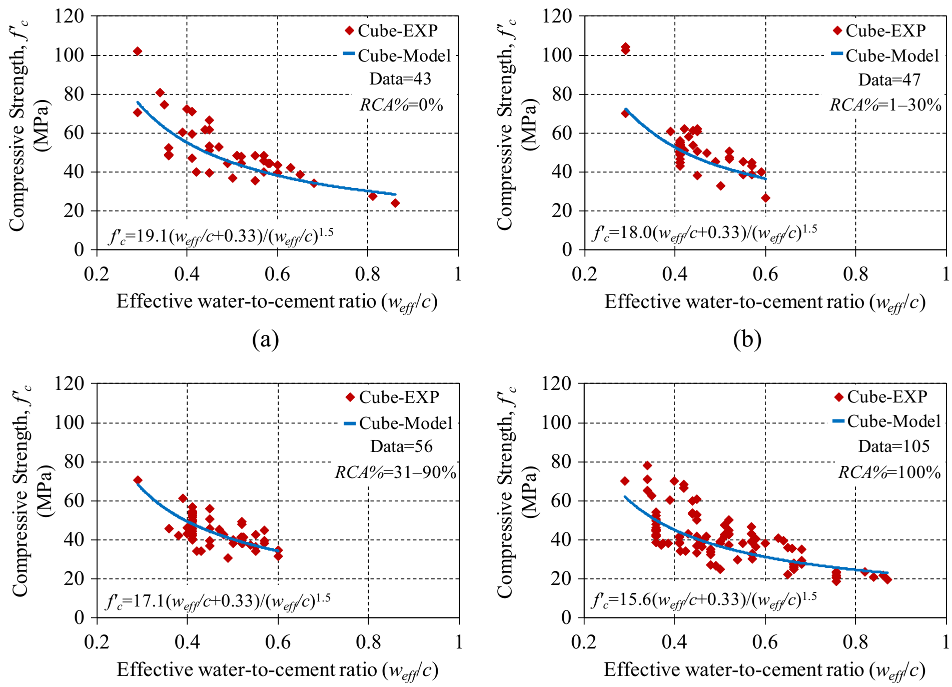

Fig. 4. Variation in compressive strength of RAC with w_{eff}/c for cube specimens: (a) $RCA\%$ = 0%, (b) $RCA\%$ = 1–30%, (c) $RCA\%$ = 31–90%, and (d) $RCA\%$ = 100%.

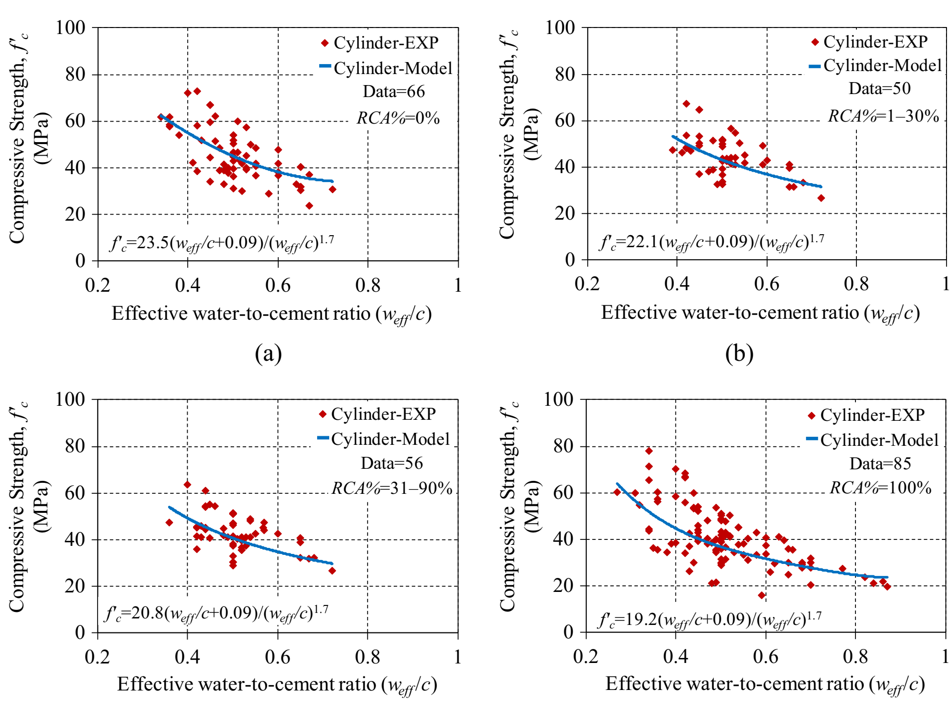

Fig. 5. Variation in compressive strength of RAC with w_{eff}/c for cylinder specimens: (a) $RCA\%$ = 0%, (b) $RCA\%$ = 1–30%, (c) $RCA\%$ = 31–90%, and (d) $RCA\%$ = 100%.

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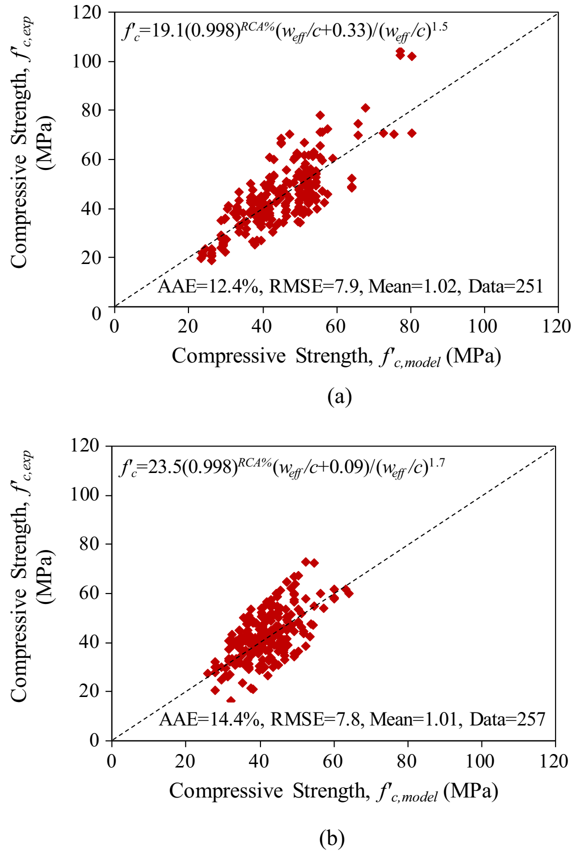

Fig. 6. Comparison of concrete compressive strengths with model predictions: (a) cubes; (b) cylinders.

Table 3 shows the prediction statistics of the proposed models together with those of the existing models. The size of the experimental database plays an important role in the reliability of the models. It can be seen in the table that the proposed models provide improved accuracy while also being applicable to a larger number of datasets than the existing models.

6.2. GEP-based formulation of the elastic modulus of RAC

As can be seen in Table 1, 16 models exist in the literature to predict the elastic modulus of RAC. In these models, the compressive strength (f'_c) is often considered as the sole parameter affecting the elastic modulus (E_c) of RACs. In the current study the following expression is proposed to predict the elastic modulus of RAC with E_c of up to 50 GPa as a function of *RCA%* and w_{eff}/c:

$$E_c(\text{GPa}) = 0.016 \times (6.1 - 0.015RCA\%) \times (5.3 - 1.7w_{eff}/c)^{3.9} \quad (12)$$

Table 4 shows the prediction statistics of the proposed model together with those of the existing models. It can be seen from the table that the models by Xiao et al. [10], Ravindrarajah and Tam [16], Bairagi et al. [17], and Wardeh et al. [28] were the best performing elastic modulus models in the literature. However, the proposed model provides better accuracy than the existing models, while also being applicable to a larger number of datasets.

6.3. GEP-based formulation of the flexural strength of RAC

The following expression is proposed to predict the flexural strength (f_r) of RAC with f_r of up to 8 MPa:

$$f_r(\text{MPa}) = 0.022 \times (1.2 - 0.002RCA\%) \times (2.3 - 0.3w_{eff}/c)^{6.9} \quad (13)$$

Table 5 shows the prediction statistics of the proposed model together with those of the four existing models. It can be seen from the table that among the existing models, those by Xiao et al. [10]

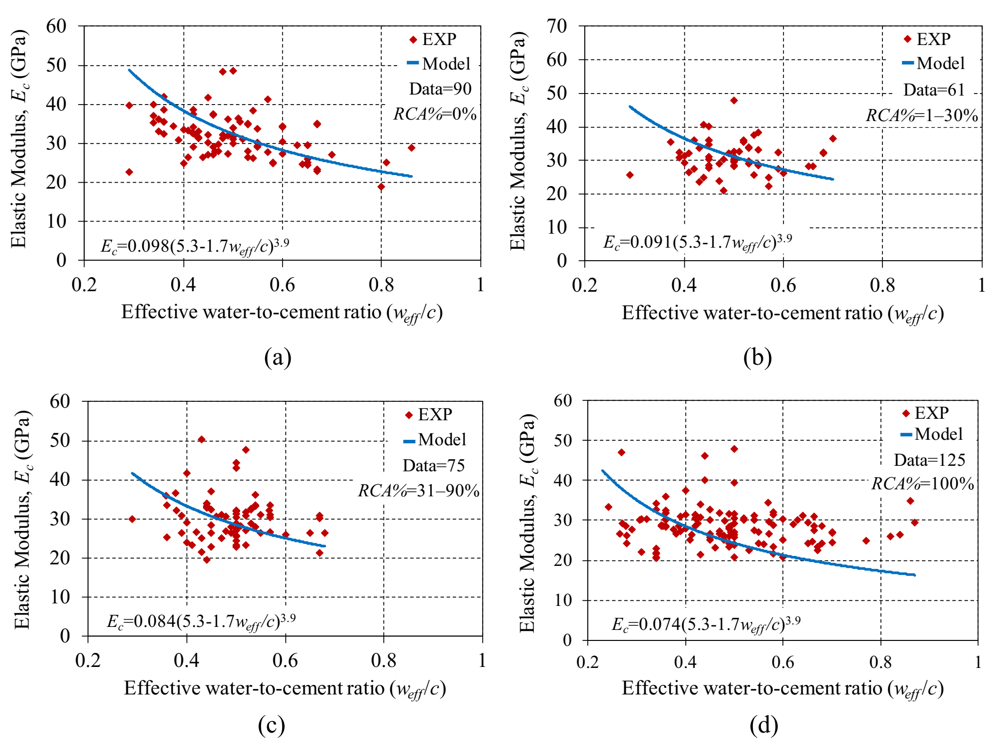

Fig. 7. Variation in elastic modulus of RAC with w_{eff}/c: (a) *RCA%* = 0%, (b) *RCA%* = 1–30%, (c) *RCA%* = 31–90%, and (d) *RCA%* = 100%.

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and Bairagi et al. [17] performed the best. It can also be seen in Table 5 that the proposed model provides further improvements to accuracy while also expanding the range of applicability.

6.4. GEP-based formulation of the splitting tensile strength of RAC

The following expression is proposed to predict the splitting tensile strength (f_{st}) of RAC with f_{st} of up to 6 MPa:

$$f_{st}(\mathrm{MPa}) = 0.012 \times (0.9 - 0.002RCA\%) \times (2.1 - 0.3w_{eff}/c)^{9.1} \quad (14)$$

Table 6 shows the prediction statistics of the proposed model together with those of the six existing models. As can be seen in the table, among existing models those by Xiao et al. [10] and Bairagi et al. [17] performed the best. It can also be seen in Table 6 that further improvements to accuracy and range of applicability are achieved by the proposed model.

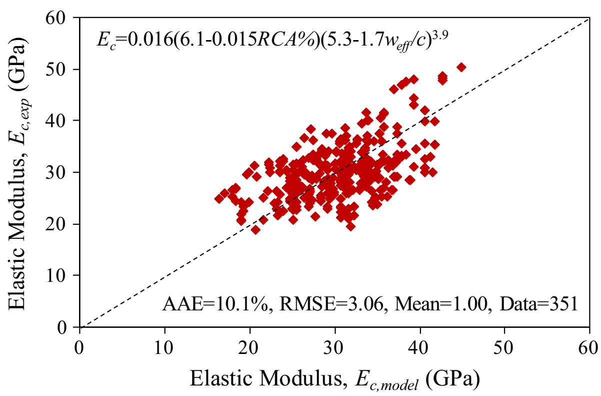

Fig. 8. Comparison of concrete elastic modulus with model predictions.

7. Parametric investigation of the proposed models

In order to further validate the proposed models, parametric analyses are performed for the proposed expressions based on the input parameters. The methodology is based on studying the variation of the model predictions with the change in a single input parameter, while the other variables are kept constant at the database average [116]. All datasets were first divided into four groups according to their recycled concrete aggregate replacement ratio (i.e., $RCA\%$ of 0%, 1–30%, 30–90%, and 100%) in order to study the effect of $RCA\%$ on the target mechanical properties. The robustness of the proposed expressions is determined by evaluating how well the predicted values agree with the mechanical properties of RAC. Figs. 4 and 5 show the variation of the compressive strength of cube ($f'_{c,cube}$) and cylinder specimens ($f'_{c,cylinder}$), respectively, with w_{eff}/c at each $RCA\%$ interval. It is well understood that the compressive strength (f'_c) of concrete decreases with increasing w_{eff}/c and the results shown in Figs. 4 and 5 are in agreement with this [8,12,24,25,117]. Figures also illustrate that the compressive strength decreases with an increase in the $RCA\%$ for a given w_{eff}/c. As can be seen in Fig. 6, which shows the comparison of the compressive strength results with the model predictions, the proposed models accurately capture the influences of w_{eff}/c and $RCA\%$ to well reproduce the test results.

Fig. 7 shows the variation of the elastic modulus of RAC with w_{eff}/c at each $RCA\%$ interval. The comparison of the expressions in Fig. 7 shows that the elastic modulus of RAC decreases with increasing w_{eff}/c, which is in agreement with previous studies [10,12,13,17,23,25]. The figure also illustrates that the elastic modulus decreases with increasing $RCA\%$ for a given w_{eff}/c. It can be seen in Fig. 8, which shows the comparison of the elastic modulus results with the model predictions, that the proposed model provides close predictions accurately capturing the influences of w_{eff}/c and $RCA\%$.

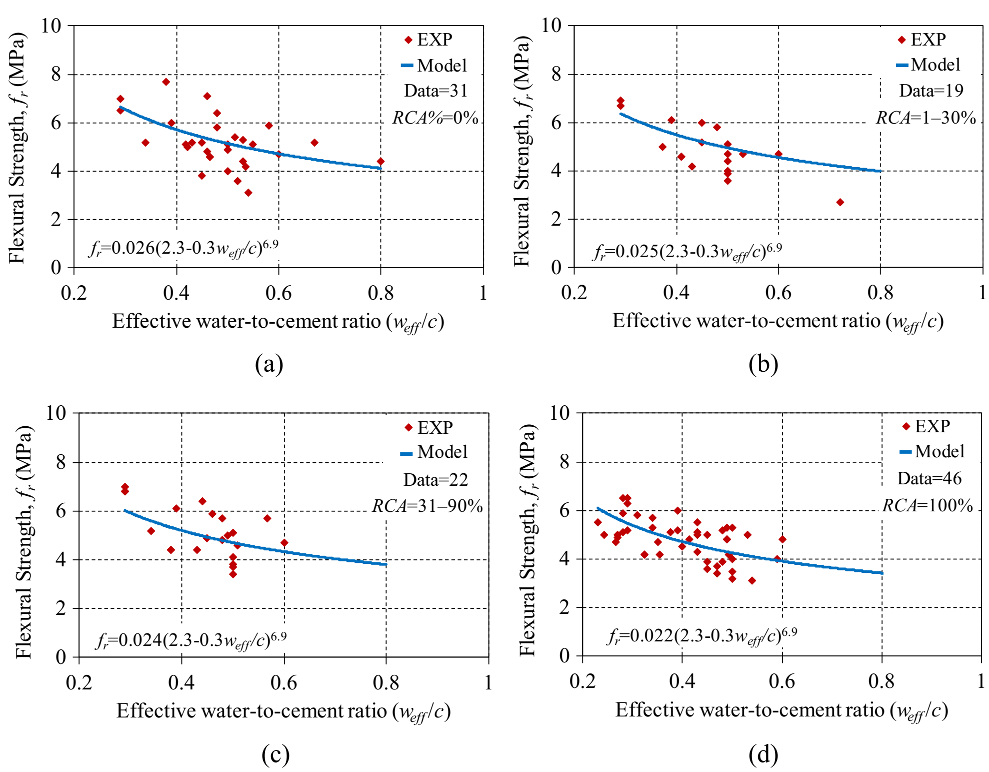

Fig. 9. Variation in flexural strength of RAC with w_{eff}/c: (a) $RCA\%$ = 0%, (b) $RCA\%$ = 1–30%, (c) $RCA\%$ = 31–90%, and (d) $RCA\%$ = 100%.

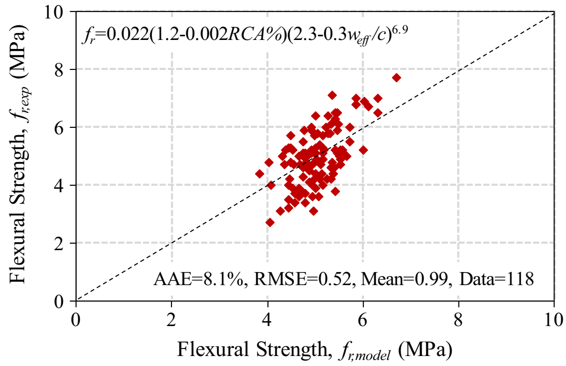

Fig. 10. Comparison of concrete flexural strength with model predictions.

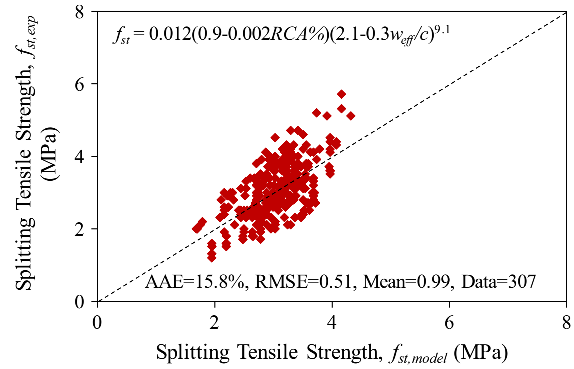

Fig. 12. Comparison of concrete splitting tensile strength with model predictions.

Fig. 9 shows the variation of the flexural strength of RAC with w_{eff}/c at each $RCA\%$ interval. The comparison of the expressions in Fig. 9 shows that the flexural strength of RAC decreases with increasing w_{eff}/c, which is in agreement with previous studies [10,23]. The figure also illustrates that the flexural strength decreases with increasing $RCA\%$ for a given w_{eff}/c. The comparisons of the experimental flexural strength results with the predictions of the proposed model are shown in Fig. 10. As can be seen in the figure, the model predicts the results closely.

Fig. 11 shows the variation of the splitting tensile strength of RAC with w_{eff}/c at each $RCA\%$ interval. The comparison of the expressions in Fig. 11 shows that the splitting tensile strength of RAC decreases with increasing w_{eff}/c, which is in agreement with the previous studies [8,23,29,117]. The figure also illustrates that the splitting tensile strength decreases with increasing $RCA\%$ for a given w_{eff}/c. The comparisons of the experimental splitting tensile strength results with the predictions of the proposed model are shown in Fig. 12. As can be seen in the figure, the model predicts the results closely.

8. Comparison of the model predictions with design code expressions

A review of the existing design codes and standards [118–124] identified a number of models that were proposed to predict the mechanical properties of NAC based on $f'_{c,cylinder}$. The details of these models are summarized in Table 7. Figs. 13(a)–(c) show the predictions of the code expressions together with those of the models proposed in this study for the elastic modulus, flexural strength, and splitting tensile strength, respectively. The comparison of the results shows that, when applied to NAC (i.e. $RCA\%$ = 0), the trends of the proposed models are in agreement with the overall trend of the existing code expressions. This observation validates the consistency of the proposed models with currently

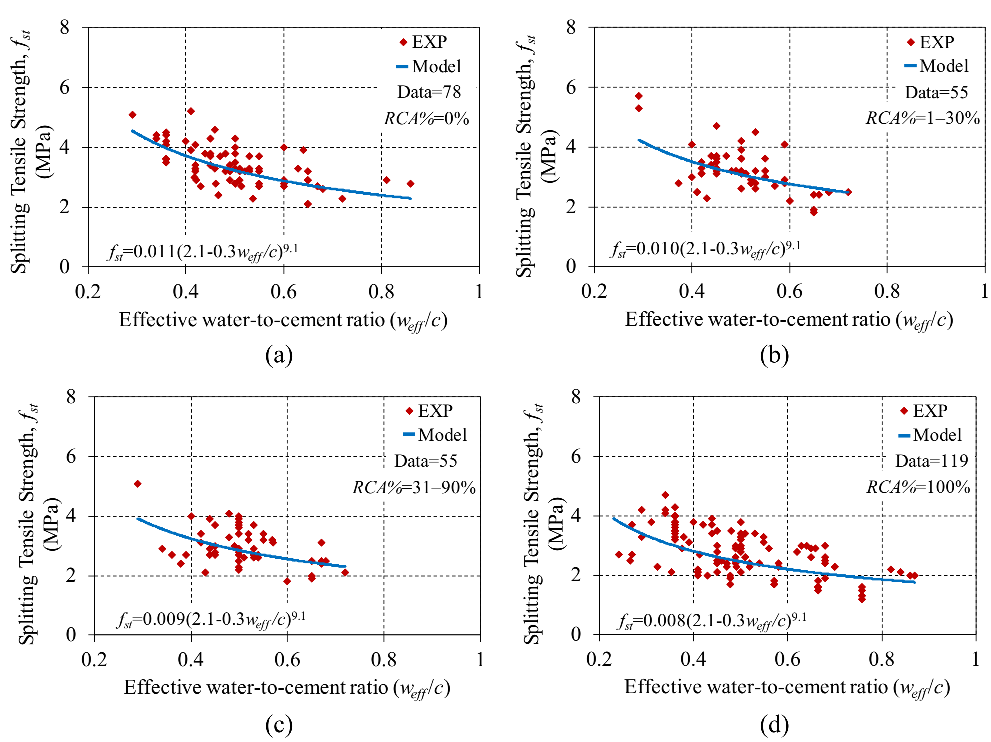

Fig. 11. Variation in splitting tensile strength of RAC with w_{eff}/c: (a) $RCA\%$ = 0%, (b) $RCA\%$ = 1–30%, (c) $RCA\%$ = 31–90%, and (d) $RCA\%$ = 100%.

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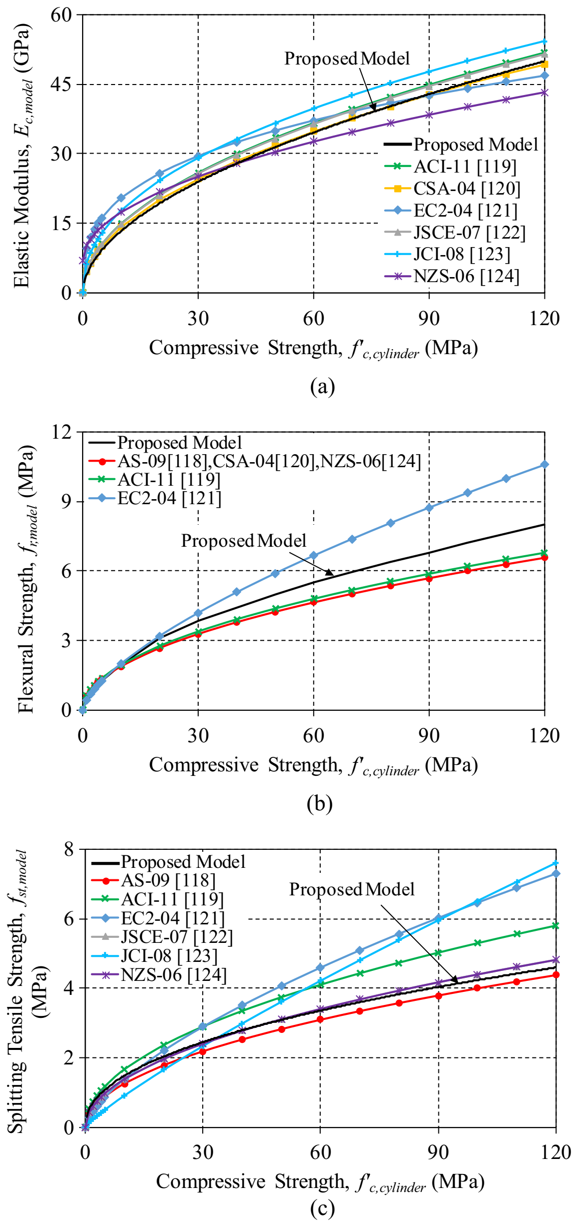

Fig. 13. Comparisons of models of the present study with models given in design codes for conventional concrete: a) elastic modulus, b) flexural strength, c) splitting tensile strength.

used expressions for NAC, which establishes a reliable baseline for the extension of the models to RAC through the incorporation of the aggregate replacement ratio.

9. Conclusions

This paper has presented new models developed using GEP technique to predict the compressive strength, elastic modulus, flexural strength, and splitting tensile strength of recycled aggregate concrete. A comprehensive database containing results of 650 compressive strength, 421 elastic modulus, 346 splitting tensile strength, and 152 flexural strength, tests of RACs reported in 69 studies and covering a wide range of parameters was assembled through an extensive review of the literature. The database was used to assess the performance of 34 existing mechanical property models of RAC reported in 21 studies. The following are the main observations and conclusions resulting from this analytical study:

1. The results of the parametric and sensitivity analyses on the database show that w_{eff}/c and $RCA\%$ are the most influential parameters on mechanical properties of RAC.
2. The proposed models provide simple formulations by accurately establishing relative contributions of the most influential parameters while also being applicable to a larger number of datasets than the existing models.
3. The comparison of the proposed models with the existing code expressions shows that the trends of the proposed models are in agreement with the overall trend of the existing code expressions when applied to NAC (i.e. $RCA\% = 0$). This observation validates the consistency of the proposed models with currently used code expressions for NAC.
4. The assessment results show that the proposed models provide accurate predictions of the compressive strength, elastic modulus, flexural strength, and splitting tensile strength of RAC, making them suitable for use in the pre-design of RACs.

Acknowledgements

The authors thank Mr Tianyu Xie for his assistance in the preparation of the test database supplied in the appendix.

Table 7
Summary of NAC mechanical property models given in current design codes.

Model	Elastic modulus (E_c) (GPa)	Flexural strength (f_r) (MPa)	Splitting tensile strength (f_{st}) (MPa)
AS 3600-09 [118]	$E_c = 4.3 \times 10^{-5}(\rho_h)^{1.5}\sqrt{f'_{cm}}$ *when $f'_{cm} \leqslant 40$MPa$E_c = (2.4(\rho_h)^{1.5}$ $\sqrt{f'_{cm}} + 12) \times 10^{-5}$ when $40 < f'_{cm} \leqslant 100$MPa	$f_r = 0.60\sqrt{f'_{c,cylinder}}$	$f_{st} = 0.4\sqrt{f'_{c,cylinder}}$
ACI 318-11 [119]	$E_c = 4.73\sqrt{f'_{c,cylinder}}$	$f_r = 0.62\sqrt{f'_{c,cylinder}}$	$f_{st} = 0.53\sqrt{f'_{c,cylinder}}$
CSA A23.3-04 [120]	$E_c = 4.5\sqrt{f'_{c,cylinder}}$	$f_r = 0.60\sqrt{f'_{c,cylinder}}$	
Eurocode 2-04 [121]	$E_c = 9.5f'^{\frac{1}{3}}_{c,cylinder}$	$f_r = 0.435f'^{2/3}_{c,cylinder}$	$f_{st} = 0.3(f'_{c,cylinder})^{2/3}$
JSCE-07 [122]	$E_c = 4.7\sqrt{f'_{c,cylinder}}$		$f_{st} = 0.44\sqrt{f'_{c,cylinder}}$
JCI-08 [123]	$E_c = 6.3f'^{0.45}_{c,cylinder}$		$f_{st} = 0.13(f'_{c,cylinder})^{0.85}$
NZS 3101:2006 [124]	$E_c = 3.32(\sqrt{f'_{c,cylinder}}) + 6.9$	$f_r = 0.60\sqrt{f'_{c,cylinder}}$	$f_{st} = 0.44\sqrt{f'_{c,cylinder}}$

In this table, f'_c, f'_{cm}, f_r, and f_{st} are in MPa, E_c is in GPa, and ρ_h is in kg/m^3.
*f'_{cm} is the mean in-situ compressive strength.

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Appendix A

Table A1
Experimental database of recycled aggregate concrete

Year of publication	Source	Geometric properties of specimens				Concrete mix properties			Properties of coarse aggregate									Physical properties of concrete		Mechanical properties of concrete			
		Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
1988	Yoda et al. [52]	C_1	C_1			0.50	2.6	0		20	20									42.8	32153		
		C_1	C_1			0.50	2.5	20		20	20									42.7	31178		
		C_1	C_1			0.50	2.5	50		20	20									41.3	31204		
		C_1	C_1			0.50	2.3	100		20	20									41.8	31589		
2000	Limbachiya et al. [53]	S_1	C_2	B_2		0.45	3.3	0		20	30		2610		2.5					51.2	27000	5.2	
		S_1	C_2	B_2		0.45	3.3	30		20	30	2400	2610	4.9	2.5					50.6	27000	5.2	
		S_1	C_2	B_2		0.45	3.3	50		20	30	2400	2610	4.9	2.5					50.8	27500	4.9	
		S_1	C_2	B_2		0.45	3.3	100		20	30	2400		4.9						50.2	26500	5.0	
		S_1	C_2	B_2		0.39	2.6	0		20	30		2610		2.5					60.3	28500	6.0	
		S_1	C_2	B_2		0.39	2.6	30		20	30	2400	2610	4.9	2.5					60.8	28000	6.1	
		S_1	C_2	B_2		0.39	2.6	50		20	30	2400	2610	4.9	2.5					61.2	28500	6.1	
		S_1	C_2	B_2		0.39	2.6	100		20	30	2400		4.9						60.2	27500	6.0	
		S_1	C_2	B_2		0.29	2.2	0		20	30		2610		2.5					70.5	30000*	7.0	
		S_1	C_2	B_2		0.29	2.2	30		20	30	2400	2610	4.9	2.5					70.2	30000	6.9	
		S_1	C_2	B_2		0.29	2.2	50		20	30	2400	2610	4.9	2.5					70.8	31000	7.0	
		S_1	C_2	B_2		0.29	2.2	100		20	30	2400		4.9						70.0	30500	7.2*	
2002	Ajdukiewicz and Kliszczewicz [54]	S_2	C_2		C_2	0.36	2.4	0	41.6	16	16							2400		48.4	30000		4.1
		S_2	C_2		C_2	0.36	2.3	100	41.6	16	16							2320		44.5	27400		4.0
		S_2	C_2		C_2	0.36	2.2	100	41.6	16	16							2230		38.7	22300		3.5
		S_2	C_2		C_2	0.36	2.4	0	50.6	16	16							2390		48.9	30900		3.6
		S_2	C_2		C_2	0.36	2.3	100	50.6	16	16							2350		46.1	28100		3.4
		S_2	C_2		C_2	0.36	2.2	100	50.6	16	16							2260		42.4	23200		3.2
		S_2	C_2		C_2	0.36	2.4	0	63.2	16	16							2390		48.9	30900		3.6
		S_2	C_2		C_2	0.36	2.3	100	63.2	16	16							2330		52.5	30100		4.0
		S_2	C_2		C_2	0.36	2.2	100	63.2	16	16							2260		50.7	24900		3.6
		S_2	C_2		C_2	0.36	2.4	0	35.6	16	16							2390		48.9	30900		3.6
		S_2	C_2		C_2	0.36	2.3	100	35.6	16	16							2370		45.2	27500		3.5
		S_2	C_2		C_2	0.36	2.2	100	35.6	16	16							2240		42.0	21300		3.2
		S_2	C_2		C_2	0.36	2.4	0	66.0	16	16							2390		48.9	30900		3.6
		S_2	C_2		C_2	0.36	2.3	100	66.0	16	16							2280		49.6	28500		3.8
		S_2	C_2		C_2	0.36	2.2	100	66.0	16	16							2210		45.1	23300		3.5
		S_2	C_2		C_2	0.36	2.7	0	72.3	16	16							2530		52.3	39800		4.2
		S_2	C_2		C_2	0.36	2.4	100	72.3	16	16							2380		54.4	36500		4.0
		S_2	C_2		C_2	0.36	2.3	100	72.3	16	16							2280		48.2	29800		3.8
2002	Gómez-Soberón [55]	C_2	C_2		C_2	0.47	2.5	0	38.4	20	20		2590		0.9					39.0	29700		3.7
		C_2	C_2		C_2	0.47	2.5	15	38.4	20	20	2410	2590	5.8	0.9					38.1	29100		3.7
		C_2	C_2		C_2	0.45	2.5	30	38.4	20	20	2410	2590	5.8	0.9					37.0	27800		3.6
		C_2	C_2		C_2	0.42	2.4	60	38.4	20	20	2410	2590	5.8	0.9					35.8	26600		3.4
		C_2	C_2		C_2	0.38	2.3	100	38.4	20	20	2410		5.8						34.5	26700		3.3
2004	Gonçalves et al. [56]	S_2				0.60	4.6	0		15	20		2670		0.5					43.5			
		S_2				0.60	4.1	100		15	20	2450		5.6						38.2			
		S_2				0.45	3.3	0		15	20		2670		0.5					61.7			
		S_2				0.45	2.9	100		15	20	2450		5.6						52.8			
		S_2				0.35	2.6	0		15	20		2670		0.5					74.4			
		S_2				0.35	2.3	100		15	20	2450		5.6						62.8			
		S_2				0.45	3.2	25		15	20		2670		0.5					60.7			
		S_2				0.45	3.1	50		15	20	2450		5.6						59.4*			
2004	Poon et al. [57]	S_1				0.57	3.1	0		20	25		2620		1.3					48.3			
		S_1				0.57	3.1	20		20	25	2330	2620	6.3	1.3					44.9			
		S_1				0.57	3.1	50		20	32	2330	2620	6.3	1.3					44.7			
		S_1				0.57	3.0	100		20	32	2330		6.3						46.8			
		S_1				0.57	3.0	0		20	32		2620		1.3					40.2			
		S_1				0.57	3.1	20		20	32	2330	2620	6.3	1.3					43.2			
		S_1				0.57	2.9	50		20	32	2330	2620	6.3	1.3					39.7			
		S_1				0.57	2.9	100		20	32	2330		6.3						43.3			
		S_1				0.57	3.0	0		20	20		2620		1.3					46.0			
		S_1				0.57	2.8	20		20	20	2330	2620	6.3	1.3					43.0			

Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens: Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Concrete mix properties: Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Properties of coarse aggregate: Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Physical properties of concrete: Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Mechanical properties of concrete: Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
		S_1				0.57	2.7	50		20	20	2330	2620	6.3	1.3					38.1			
		S_1				0.57	2.9	100		20	20	2330		6.3						39.1			
2004	Lin et al. [58]	C_1				0.50	2.4	100		25	20									30.2			
		C_1				0.50	2.3	100		25	20									36.2			
		C_1				0.70	3.3	100		25	20									27.7			
		C_1				0.70	3.2	100		25	20									20.4			
2006	Xiao et al. [10]	S_1				0.43	3.0	0		32	19		2820		0.4			2402		35.9*			
		S_1				0.43	2.9	33		32	19	2520	2820	9.3	0.4			2368		34.1			
		S_1				0.43	2.8	53		32	19	2520	2820	9.3	0.4			2345		29.6*			
		S_1				0.43	2.8	72		32	19	2520	2820	9.3	0.4			2316		30.3*			
		S_1				0.43	2.7	100		32	19	2520		9.3				2280		26.7*			
2006	Wei [59]	S_2	C_1	B_1	C_1	0.42	3.0	0		32	32		2786		0.3					36.8*	31880	5.0	2.9
		S_2	C_1	B_1	C_1	0.37	2.9	30		32	32	2442	2786	6.0	0.3					37.2*	29132	5.0	2.8
		S_2	C_1	B_1	C_1	0.34	2.8	50		32	32	2442	2786	6.0	0.3					37.8*	26620	5.2	2.9
		S_2	C_1	B_1	C_1	0.38	2.0	70		32	32	2442	2786	6.0	0.3					36.7*	25433*	5.1*	2.7*
		S_2	C_1	B_1	C_1	0.27	2.7	100		32	32	2442		6.0						35.2*	25111	4.9	2.7
2007	Etxeberria et al. [60]	C_2	C_2		C_2	0.55	4.0	0		25	19		2670		0.9					42.0	33700		2.7
		C_2	C_2		C_2	0.55	3.9	25		25	19	2430	2670	4.4	0.9					42.0	33200		3.0
		C_2	C_2		C_2	0.52	3.6	50		25	19	2430	2670	4.4	0.9					41.0	31800		3.2
		C_2	C_2		C_2	0.50	3.5	100		25	19	2430		4.4						40.0	27000		3.2
2007	Etxeberria et al. [61]	S_2	C_2		C_2	0.55	4.0	0		25	19		2670		0.9			2420		35.5	32437		2.8
		S_2	C_2		C_2	0.55	3.9	25		25	19	2430	2670	4.5	0.9			2400		38.8	31427		3.0
		S_2	C_2		C_2	0.52	3.6	50		25	19	2430	2670	4.5	0.9			2390		39.4	29758		3.4
		S_2	C_2		C_2	0.50	3.5	100		25	19	2430		4.5				2340		38.3	27063		2.8
2007	Evangelista and De Brito [62]	S_2	C_2		C_2	0.41	3.1	0		20	25		2564		0.8					59.4	35500		3.9
		S_2				0.42	3.2	10		20	25	2165	2564	6.8	0.8					62.2			
		S_2				0.43	3.4	20		20	25	2165	2564	6.8	0.8					58.4			
		S_2	C_2		C_2	0.44	3.5	30		20	25	2165	2564	6.8	0.8					61.3	34200		3.7
		S_2				0.45	3.7	50		20	25	2165	2564	6.8	0.8					60.8*			
		S_2	C_2		C_2	0.45	4.4	100		20	25	2165		6.8						61.0	28900		3.0
2007	Poon et al. [63]	S_1				0.51	2.6	0		20	20		2620		1.1					48.6			
		S_1				0.49	2.5	20		20	20	2570	2620	3.5	1.1					45.3			
		S_1				0.48	2.5	50		20	20	2570	2620	3.5	1.1					42.5			
		S_1				0.46	2.5	80		20	20	2570	2620	3.5	1.1					39.2*			
		S_1				0.45	2.5	100		20	20	2570		3.5						37.1			
2007	Ajdukiewicz and Kliszczewicz [64]	C_2	C_2		C_2	0.49	4.7	0		16	20	2270						2350		37.7	31900		2.9
		C_2	C_2		C_2	0.49	3.9	100		16	20	2270						2250		34.6	25900		2.6
		C_2	C_2		C_2	0.36	2.4	0		16	20	2270						2380		57.9	35600		3.5
		C_2	C_2		C_2	0.36	2.2	100		16	20	2270						2310		56.4	31800		3.3
		C_2	C_2		C_2	0.49	3.7	0		16	25	2780						2390		39.8	27300		3.2
		C_2	C_2		C_2	0.49	4.4	100		16	25	2780						2310		40.1	24300		2.9
		C_2	C_2		C_2	0.36	2.4	0		16	25	2780						2390		58.3	32500		4.4
		C_2	C_2		C_2	0.36	2.3	100		16	25	2780						2290		60.2	28500		4.3
		C_2	C_2		C_2	0.49	5.1	0		16	16	2565						2550		40.1	36200		3.4
		C_2	C_2		C_2	0.49	4.2	100		16	16	2565						2400		35.3	31700		3.0
		C_2	C_2		C_2	0.36	2.7	0		16	16	2565						2530		61.8	41900		4.5
		C_2	C_2		C_2	0.36	2.4	100		16	16	2565						2430		57.5	35900		3.7
2007	Hu [65]	S_2	C_1	B_1	C_1	0.47	3.3	0		32	22		2788		0.3					31.2*	30296	4.6	2.4
		S_2	C_1	B_1	C_1	0.41	3.3	30		32	22	2449	2788	6.0	0.3					31.0*	28620	4.6	2.5
		S_2	C_1	B_1	C_1	0.38	3.2	50		32	22	2449	2788	6.0	0.3					29.3*	25119	4.4	2.4
		S_2	C_1	B_1	C_1	0.36	3.1	70		32	22	2449	2788	6.0	0.3					28.4*	23378*	4.4*	2.4*
		S_2	C_1	B_1	C_1	0.32	3.0	100		32	22	2449		6.0						27.2*	23297	4.2	2.3
2007	Kou et al. [66]	S_1	C_1		C_1	0.45	2.8	0		20	19		2620		1.1					66.8	38700		3.4
		S_1	C_1		C_1	0.45	2.8	20		20	19	2570	2620	3.5	1.1					62.4	29100		3.2
		S_1	C_1		C_1	0.45	2.7	50		20	19	2570	2620	3.5	1.1					55.8	26000		3.0
		S_1	C_1		C_1	0.45	2.7	100		20	32	2570		3.5						42.0	23400		2.8
		S_1	C_1		C_1	0.55	2.6	0		20	32		2620		1.1					48.6	30000		3.3
		S_1	C_1		C_1	0.55	2.5	20		20	32	2570	2620	3.5	1.1					45.3	28800		3.2
		S_1	C_1		C_1	0.55	2.5	50		20	32	2570	2620	3.5	1.1					42.5	26300		3.2
		S_1	C_1		C_1	0.55	2.5	100		20	32	2570		3.5						38.1	21700		3.1

(*continued on next page*)

Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens: Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Concrete mix properties: Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Properties of coarse aggregate: Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Physical properties of concrete: Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Mechanical properties of concrete: Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
2007	Rahal [24]	S_1	C_2			0.65	3.1	0		19	25		2860		0.7					21.8*	11400*		
		S_1	C_2			0.65	3.1	100		19	25	2390		4.4						22.1	12400*		
		S_1	C_2			0.50	2.9	0		19	25		2860		0.7					26.7*	14900*		
		S_1	C_2			0.50	2.9	100		19	25	2390		4.4						25.1	11300*		
		S_1	C_2			0.48	2.8	0		19	25		2860		0.7					28.9*	15700*		
		S_1	C_2			0.48	2.8	100		19	25	2390		4.4						27.2	14900*		
		S_1	C_2			0.43	2.6	0		19	25		2860		0.7					31.1*	17800*		
		S_1	C_2			0.43	2.6	100		19	25	2390		4.4						28.7*	14700*		
		S_1	C_2			0.40	2.4	0		19	19		2860		0.7					33.7*	17100*		
		S_1	C_2			0.40	2.4	100		19	19	2390		4.4						29.5*	13400*		
2007	Wang [67]	S_2				0.54	3.1	0		32	25		2840		0.4					26.8*			
		S_2				0.35	3.1	100		32	25	2512		6.3						24.6*			
		S_2				0.49	3.1	100		32	25	2670		1.8						26.9			
		S_2				0.46	2.7	0		32	25		2840		0.4					34.3*			
		S_2				0.31	2.7	100		32	32	2512		6.3						30.2*			
		S_2				0.43	2.7	100		32	32	2670		1.8						34.2			
		S_2				0.42	2.4	0		32	32		2840		0.4					38.6*			
		S_2				0.28	2.4	100		32	32	2512		6.3						35.5*			
		S_2				0.39	2.4	100		32	32	2670		1.8						38.4			
2008	Casuccio et al. [68]	C_1	C_1			0.70	4.1	0		30	10		2700		0.5		28.0			18.1*	27100		
		C_1	C_1			0.67	3.9	100		30	10	2520		3.8		34				18.0*	23400		
		C_1	C_1			0.67	3.9	100		30	10	2510		3.9		39				15.4*	22600		
		C_1	C_1			0.35	3.1	0		30	10		2700		0.5		28.0			37.5*	33100		
		C_1	C_1			0.35	4.3	100		30	10	2520		3.8		34				36.4	28800		
		C_1	C_1			0.36	2.1	100		30	10	2510		3.9		39				35.7	28300		
		C_1	C_1			0.34	2.1	0		30	19		2700		0.5		28.0			48.4*	39900		
		C_1	C_1			0.34	1.9	100		30	19	2520		3.8		34				44.4	34200		
		C_1	C_1			0.34	2.2	100		30	30	2510		3.9		39				43.8	32700		
2008	Hu [69]	S_2	C_1	B_1	C_1	0.47	3.3	0		32	22		2788		0.3					31.2*	30296	4.6	2.4
		S_2	C_1	B_1	C_1	0.41	3.3	30		32	22	2449	2788	6.0	0.3					31.0*	28620	4.6	2.5
		S_2	C_1	B_1	C_1	0.38	3.2	50		32	22	2449	2788	6.0	0.3					29.3*	25119	4.4	2.4
		S_2	C_1	B_1	C_1	0.36	3.1	70		32	22	2449	2788	6.0	0.3					28.4*	23378*	4.4*	2.4*
		S_2	C_1	B_1	C_1	0.32	3.0	100		32	25	2449		6.0						27.2*	23297	4.2	2.3
2008	Kou et al. [70]	C_1	C_1		C_1	0.55	2.6	0		20	20		2620		1.1					48.6	30300		3.7
		C_1	C_1		C_1	0.55	2.6	20		20	20	2580	2620	3.5	1.1					45.3	28650		3.6
		C_1	C_1		C_1	0.55	2.5	50		20	20	2580	2620	3.5	1.1					42.5	26400		3.4
		C_1	C_1		C_1	0.55	2.5	100		20	20	2580		3.5						38.1	24200		3.3
		C_1	C_1		C_1	0.50	2.6	0		20	20		2620		1.1					54.1	31100		3.8
		C_1	C_1		C_1	0.50	2.6	20		20	20	2580	2620	3.5	1.1					51.7	29570		3.6
		C_1	C_1		C_1	0.50	2.6	50		20	20	2580	2620	3.5	1.1					47.1	27510		3.6
		C_1	C_1		C_1	0.50	2.6	100		20	20	2580		3.5						43.4	25670		3.4
		C_1	C_1		C_1	0.45	2.8	0		20	20		2620		1.1					66.8	32210		3.8
		C_1	C_1		C_1	0.45	2.8	20		20	20	2580	2620	3.5	1.1					62.4*	30370		3.7
		C_1	C_1		C_1	0.45	2.7	50		20	20	2580	2620	3.5	1.1					56.8*	28540		3.7
		C_1	C_1		C_1	0.45	2.5	100		20	20	2580		3.5						52.1	26600		3.5
		C_1	C_1		C_1	0.40	2.9	0		20	20		2620		1.1					72.3	33470		4.2
		C_1	C_1		C_1	0.40	2.8	20		20	20	2580	2620	3.5	1.1					69.6*	31400		4.1
		C_1	C_1		C_1	0.40	2.8	50		20	20	2580	2620	3.5	1.1					65.3*	29200		4.0
		C_1	C_1		C_1	0.40	2.8	100		20	20	2580		3.5						58.5	27850		3.8
2008	Yang et al. [71]	C_1	C_1	B_2	C_1	0.50	2.9	0		25	20		2600		1.4					39.5	31722	4.0	4.3
		C_1	C_1	B_2	C_1	0.50	2.9	30		25	20	2530	2600	1.9	1.4					36.7	30374	4.0	4.2
		C_1	C_1	B_2	C_1	0.50	2.9	50		25	20	2530	2600	1.9	1.4					38.0	30520	3.7	4.0
		C_1	C_1	B_2	C_1	0.50	2.8	100		25	32	2530		1.9						36.0	29223	3.5	3.8
		C_1	C_1	B_2	C_1	0.50	2.8	30		25	32		2600		1.4					32.6	28361	3.6	3.6
		C_1	C_1	B_2	C_1	0.50	2.8	50		25	32	2400	2600	6.2	1.4					30.4	25885	3.4	3.4
		C_1	C_1	B_2	C_1	0.50	2.7	100		25	32	2400		6.2						29.5	23717	3.2	3.2
2008	Zhou et al. [72]	S_1				0.58	3.2	0		32	32		2970		0.8					44.6			
		S_1				0.52	3.2	50		32	22	2720	2970	4.8	0.8					41.4			
		S_1				0.45	3.2	100		32	22	2720		4.8						40.7			
		S_1				0.52	3.2	50		32	22	2650	2970	4.6	0.8					38.3			
		S_1				0.46	3.2	100		32	22	2650		4.6						36.6			
		S_1				0.52	3.2	50		32	22	2880	2970	4.4	0.8					41.2			
		S_1				0.47	3.2	100		32	22	2880		4.4						40.3			
2009	Domingo-Cabo et al. [73]	C_2	C_2			0.41	2.6	0		20	20		2647		1.0		27.8		2360	42.3	33308		
		C_2	C_2			0.39	2.5	20		20	20	2338	2647	5.2	1.0	40.2	27.8		2350	47.4	32360		
		C_2	C_2			0.36	2.5	50		20	20	2338	2647	5.2	1.0	40.2	27.8		2340	47.3	33516		
		C_2	C_2			0.32	2.3	100		20	20	2338		5.2		40.2			2320	54.8	30337		

Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens: Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Concrete mix properties: Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Properties of coarse aggregate: Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Physical properties of concrete: Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Mechanical properties of concrete: Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
2009	Padmini et al. [74]	S_2				0.52	2.9	0		22	20									48.0			
		S_2				0.52	2.9	10		22	20									46.9			
		S_2				0.52	2.8	20		22	20									47.7			
		S_2				0.52	2.8	30		22	20									50.8			
		S_2				0.52	2.8	40		22	20									48.0			
		S_2				0.52	2.8	50		22	25									49.5			
		S_2				0.52	2.7	100		22	25									50.3			
		S_2	C_2	B_2		0.54	3.2	0		22	25									23.5*	36200	3.1	
		S_2	C_2	B_2		0.54	3.1	25		22	25									21.6*	34100	2.9*	
		S_2	C_2	B_2		0.54	3.1	100		22	20									20.5*	32100	3.1	
2009	Yang et al. [75]	S_2			C_1	0.76	4.5	100		30	32									21.1*			1.2
		S_2			C_1	0.76	4.5	100		30	32									22.0			1.6
		S_2			C_1	0.76	4.5	100		30	32									23.1			1.5
		S_2			C_1	0.76	4.5	100		30	32									23.5			1.3
		S_2			C_1	0.76	4.5	100		30	32									20.4			1.5
		S_2			C_1	0.76	4.5	100		30	32									18.9			1.3
		S_2			C_1	0.76	4.5	100		30	32									21.2			1.5
		S_2			C_1	0.66	3.9	100		30	32									25.7			1.6
		S_2			C_1	0.66	3.9	100		30	32									28.0			1.6
		S_2			C_1	0.66	3.9	100		30	32									25.1			1.5
		S_2			C_1	0.66	3.9	100		30	32									27.5			1.6
		S_2			C_1	0.66	3.9	100		30	32									26.1			1.5
		S_2			C_1	0.66	3.9	100		30	32									27.4			1.1*
		S_2			C_1	0.66	3.9	100		30	32									27.7			1.6
		S_2			C_1	0.66	3.9	100		30	32									25.0			1.8
		S_2			C_1	0.57	3.3	100		30	32									30.5			1.7
		S_2			C_1	0.57	3.3	100		30	30									32.7			1.7
		S_2			C_1	0.57	3.3	100		30	30									32.8			1.7
		S_2			C_1	0.57	3.3	100		30	30									33.1			1.8
		S_2			C_1	0.48	2.7	100		30	30									35.3			2.0
		S_2			C_1	0.48	2.7	100		30	30									35.2			1.4*
		S_2			C_1	0.48	2.7	100		30	30									32.5			1.9
		S_2			C_1	0.48	2.7	100		30	30									33.8			1.7
		S_2			C_1	0.41	2.2	100		30	30									41.9			2.1
		S_2			C_1	0.41	2.2	100		30	30									38.4			2.0
		S_2			C_1	0.41	2.2	100		30	30									38.7			2.1
		S_2			C_1	0.41	2.2	100		30	30									41.2			2.2
2009	Ye [76]	S_2	C_1	B_1	C_1	0.54	3.1	0		32	32		2840		0.4					26.8*	28500	4.2	2.3
		S_2	C_1	B_1	C_1	0.35	3.1	100		32	32	2512		6.3						24.6*	22180	4.2	2.1
		S_2	C_1	B_1	C_1	0.49	3.1	100		32	32	2670		1.8						26.9	27900	4.2	2.3
		S_2	C_1	B_1	C_1	0.46	3.3	0		32	32		2840		0.4					34.3*	31230	4.8	2.8
		S_2	C_1	B_1	C_1	0.27	3.3	100		32	32	2512		6.3						30.2*	23860	4.7	2.5
		S_2	C_1	B_1	C_1	0.41	3.3	100		32	32	2670		1.8						34.2	31070	4.8	2.7
		S_2	C_1	B_1	C_1	0.42	3.0	0		32	32		2840		0.4					38.6*	32500	5.1	3.0
		S_2	C_1	B_1	C_1	0.24	3.0	100		32	32	2512		6.3						35.5*	25200	5.0	2.7
		S_2	C_1	B_1	C_1	0.38	3.0	100		32	32	2670		1.8						38.4	31800	5.1	2.9
2010	Corinaldesi [25]	S_1	C_1			0.40	3.1	50		12	30	2420	2570	6.8	3.0					43.3	28600		
		S_1	C_1			0.45	3.1	50		12	30	2400	2570	6.8	3.0					39.6	28600		
		S_1	C_1			0.50	3.2	50		12	30	2400	2570	6.8	3.0					38.1	27200		
		S_1	C_1			0.55	3.2	50		12	30	2400	2570	6.8	3.0					34.5	26700		
		S_1	C_1			0.60	3.3	50		12	30	2400	2570	6.8	3.0					31.6	26400		
		S_1	C_1			0.40	3.1	50		22	30	2420	2570	8.8	3.0					46.1	32700		
		S_1	C_1			0.45	3.1	50		22	30	2420	2570	8.8	3.0					45.8	33300		
		S_1	C_1			0.50	3.2	50		22	30	2420	2570	8.8	3.0					39.9	27700		
		S_1	C_1			0.55	3.3	50		22	20	2420	2570	8.8	3.0					36.3	24000		
		S_1	C_1			0.60	3.3	50		22	20	2420	2570	8.8	3.0					34.7	22900		
2010	Kumutha and Vijai [77]	S_1	C_2	B_1	C_2	0.50	3.5	0		20	20		2870						2610	28.3*	27665	4.9	3.3
		S_1	C_2	B_1	C_2	0.50	3.5	20		20	20	2400	2870						2559	27.2*	27078	3.9	3.1
		S_1	C_2	B_1	C_2	0.50	3.5	40		20	20	2400	2870						2510	26.5*	26222	2.9*	2.8
		S_1	C_2	B_1	C_2	0.50	3.5	60		20	20	2400	2870						2488	25.4*	25527	2.7*	2.7
		S_1	C_2	B_1	C_2	0.50	3.5	80		20	20	2400	2870						2478	25.1*	25250*	2.6*	2.2*
		S_1	C_2	B_1	C_2	0.50	3.5	100		20	20	2400							2454	20.4*	22681	2.4*	2.1
		S_1	C_2	B_1	C_2	0.50	3.8	20		20	20	2630	2870						2602	26.4*	25927	4.4	2.6
		S_1	C_2	B_1	C_2	0.50	4.1	40		20	20	2630	2870						2582	25.9*	25782	4.1	2.5
		S_1	C_2	B_1	C_2	0.50	4.5	60		20	20	2630	2870						2558	23.5*	25113	3.8	2.3
		S_1	C_2	B_1	C_2	0.50	4.8	80		20	20	2630	2870						2538	15.4*	18048*	3.4*	2.0*

(*continued on next page*)

Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens				Concrete mix properties			Properties of coarse aggregate									Physical properties of concrete		Mechanical properties of concrete			
		Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
2010	Radonjanin et al. [78]	C_1	C_1	B_1	C_1	0.51	3.6	0		32	20		2671		0.3		29.2			43.4	35550	5.4	2.7
		C_1	C_1	B_1	C_1	0.57	3.6	50		32	20	2489	2671	2.4	0.3	34	29.2			45.2	32250	5.7	3.2
		C_1	C_1	B_1	C_1	0.62	3.6	100		32	20	2489		2.4		34				45.7*	29100	5.2*	2.8
2010	Zega and Di Maio [79]	S_1	C_2		C_2	0.65	3.3	0		19	20		2720		0.2		25.0			20.2*	25000		2.1
		S_1	C_2		C_2	0.65	3.2	25		19	20	2440	2720	5.8	0.2	33.6	25.0			18.5*	24900		1.9
		S_1	C_2		C_2	0.65	3.1	50		19	20	2440	2720	5.8	0.2	33.6	25.0			18.0*	23000		1.9
		S_1	C_2		C_2	0.65	3.1	75		19	20	2440	2720	5.8	0.2		25.0			16.5*	20500*		1.4*
		S_1	C_2		C_2	0.42	2.7	0		19	20		2720		0.2	33.6	25.0			40.0	33500		3.2
		S_1	C_2		C_2	0.42	2.7	25		19	20	2440	2720	5.8	0.2	33.6	25.0			33.0*	31500		3.1
		S_1	C_2		C_2	0.42	2.6	50		19	20	2440	2720	5.8	0.2	33.6	25.0			34.5	31000		3.1
		S_1	C_2		C_2	0.42	2.5	75		19	20	2440	2720	5.8	0.2	33.6	25.0			34.0*	30000*		2.9*
2011	Belén et al. [80]	C_1	C_1		C_1	0.65	3.4	0		16	20		2730		2.5				2340	31.9	29569		2.9
		C_1	C_1		C_1	0.66	3.3	20		16	20	2400	2730	5.0	2.5				2330	31.7	28190		2.4
		C_1	C_1		C_1	0.68	3.1	50		16	20	2400	2730	5.0	2.5				2310	32.4	26352		2.5
		C_1	C_1		C_1	0.68	2.8	100		16	20	2400		5.0					2270	30.1	24261		2.6
		C_1	C_1		C_1	0.50	2.6	0		16	20		2730		2.5				2360	44.8	33875		2.8
		C_1	C_1		C_1	0.51	2.5	20		16	20	2400	2730	5.0	2.5				2330	43.7	32594		3.1
		C_1	C_1		C_1	0.53	2.3	50		16	20	2400	2730	5.0	2.5				2310	37.5	28817		2.9
		C_1	C_1		C_1	0.56	2.1	100		16	20	2400		5.0					2270	40.5	23994		2.9
2011	Fathifazl et al. [81]	C_2				0.45	1.9	0		19	25	2420		5.4	0.9				2324	35.2*			
		C_2				0.45	3.4	64		19	25	2420	2740	5.4	0.9				2303	41.4*			
		C_2				0.45	2.3	100		19	25	2420	2740	5.4					2290	43.9			
		C_2				0.45	2.1	0		19	25	2500		3.3	0.9				2322	34.1			
		C_2				0.45	3.1	64		19	25	2500	2740	3.3	0.9				2364	44.8*			
		C_2				0.45	2.5	100		19	25	2500	2740	3.3					2348	45.9			
2011	González-Fonteboa et al. [82]	C_2	C_2		C_2	0.65	3.4	0		16	20		2720		2.0		23.0		2340	31.9	29569		2.9
		C_2	C_2		C_2	0.65	3.3	20		16	20	2400	2720	5.0	2.0	34	23.0		2320	31.7	28190		2.4
		C_2	C_2		C_2	0.65	3.1	50		16	20	2400	2720	5.0	2.0	34	23.0		2300	32.4	26352		2.5
		C_2	C_2		C_2	0.65	2.8	100		16	20	2400		5.0		34			2270	30.1	24261		2.6
		C_2	C_2		C_2	0.50	2.6	0		16	20		2720		2.0		23.0		2360	44.8	33875		2.8
		C_2	C_2		C_2	0.50	2.5	20		16	20	2400	2720	5.0	2.0	34	23.0		2330	43.7	32594		3.1
		C_2	C_2		C_2	0.50	2.8	50		16	20	2400	2720	5.0	2.0	34	23.0		2310	37.5	28817		2.9
		C_2	C_2		C_2	0.50	2.1	100		16	20	2400		5.0		34			2270	40.5	23994		2.9
2011	Rao et al. [83]	C_2	C_2		C_2	0.43	3.1	0		20	20		2620		1.1		21.6	2146		51.8	31220	5.2	2.7
		C_2	C_2		C_2	0.43	3.0	25		20	20	2661	2620	1.9	1.1		21.6	2329		47.0	23570	4.2	2.3
		C_2	C_2		C_2	0.43	2.9	50		20	20	2602	2620	2.6	1.1		21.6	2302		46.0	21540	4.4	2.1
		C_2	C_2		C_2	0.43	2.8	100		20	20	2510		3.9		38.8		2175		42.5	20350*	5.0	2.0
2011	Somna et al. [84]	C_1				0.45	2.3	0		19	25		2730		0.45		23			44.4			
		C_1				0.45	2.3	100		19	25	2490		4.8		37				41.0			
		C_1				0.55	2.9	0		19	25		2730		0.45		23			36.7			
		C_1				0.55	2.9	100		19	25	2490		4.8		37				33.3			
		C_1				0.65	3.5	0		19	25		2730		0.45		23			30.4			
		C_1				0.65	3.5	100		19	25	2490		4.8		37				24.8			
2012	Abd Elhakam et al. [85]	S_2			C_1	0.60	4.6	0		19	20									25.0*			2.7
		S_2			C_1	0.60	4.6	25		19	20									26.7			2.2
		S_2			C_1	0.60	4.5	50		19	20									21.5*			1.8
		S_2			C_1	0.60	4.5	75		19	20									21.4*			1.4*
		S_2			C_1	0.60	4.4	100		19	20									20.0*			1.2*
		S_2			C_1	0.45	2.6	0		19	20									39.5			3.4
		S_2			C_1	0.45	2.6	25		19	20									38.3			3.1
		S_2			C_1	0.45	2.5	50		19	20									37.0			2.7
		S_2			C_1	0.45	2.5	75		19	19									35.0*			2.5*
		S_2			C_1	0.45	2.5	100		19	19									33.3			2.1
2012	Cui et al. [86]	S_2				0.49	3.1	0		25	16		2710		0.8					44.3			
		S_2				0.37	3.0	100	26.3	25	16	2490		2.9						37.6			
		S_2				0.43	3.0	100	42.7	25	16	2570		2.9						43.3			
		S_2				0.36	2.9	100	42.7	25	16	2440		5.6						42.6			
		S_2				0.36	2.9	100	65.3	25	16	2470		5.3						44.7			
2012	Hoffmann et al. [26]	C_2	C_2	B_2		0.53	6.5	0		32	15		2650		0.2					39.3	26500	4.4	
		C_2	C_2	B_2		0.43	5.4	100		32	15	2263		6.0						33.2*	21450	4.3	
		C_2	C_2	B_2		0.49	5.1	100		32	15	2283		4.2						35.6	23400	4.8	
		C_2	C_2	B_2		0.53	5.1	100		32	15	2292		4.3						34.6	22550	5.0	
		C_2	C_2	B_2		0.60	5.3	100		32	15	2301		5.0						37.3	20700	5.1*	

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Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens: Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Concrete mix properties: Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Properties of coarse aggregate: Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Physical properties of concrete: Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Mechanical properties of concrete: Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f_r) (MPa)	Splitting tensile strength (f_{st}) (MPa)
		C_2	C_2	B_2		0.54	6.4	90		32	15	2609	2650	1.5	0.2					45.4*	32433*	4.4*	
		C_2	C_2	B_2		0.46	5.9	60		32	15	2518	2650	2.7	0.2					54.3	30667	5.9	
		C_2	C_2	B_2		0.44	5.8	60		32	15	2584	2650	1.6	0.2					54.4	33333	6.4	
		C_2	C_2	B_2		0.45	6.4	25		32	32	2594	2650	1.6	0.2					53.4	34800	6.0	
2012	Li and Xiao [87]	S_1	C_1			0.43	3.0	0		32	25									34.8*	26568		
		S_1	C_1			0.47	2.9	30		32	32									31.9*	26552		
		S_1	C_1			0.49	2.8	50		32	32									30.6	26333		
		S_1	C_1			0.54	2.7	100		32	32									29.7	25650		
2012	Limbachiya et al. [88]	C_2	C_2			0.66	4.6	0		20	22		2510		1.4					21.0*	19500*		
		C_2	C_2			0.66	4.6	30		20	22	2340	2510	5.3	1.4					20.0*	17500*		
		C_2	C_2			0.61	4.3	50		20	22	2340	2510	5.3	1.4					19.0*	15500*		
		C_2	C_2			0.58	4.0	100		20	22	2340		5.3						18.0*	12500*		
		C_2	C_2			0.55	3.8	0		20	22		2510		1.4					21.0*	18800*		
		C_2	C_2			0.55	3.8	30		20	22	2340	2510	5.3	1.4					23.0*	17000*		
		C_2	C_2			0.51	3.5	50		20	22	2340	2510	5.3	1.4					24.0*	16500*		
		C_2	C_2			0.48	3.4	100		20	22	2340		5.3						21.0	14000*		
		C_2	C_2			0.50	3.5	0		20	22		2510		1.4					31.0	23500*		
		C_2	C_2			0.50	3.5	30		20	22	2340	2510	5.3	1.4					25.0*	18500*		
		C_2	C_2			0.47	3.2	50		20	22	2340	2510	5.3	1.4					29.0*	17000*		
		C_2	C_2			0.44	3.0	100		20	22	2340		5.3						30.0	16500*		
		C_2	C_2			0.48	3.3	0		20	22		2510		1.4					33.0	22000*		
		C_2	C_2			0.48	3.3	30		20	12	2340	2510	5.3	1.4					39.0	21000		
		C_2	C_2			0.44	3.1	50		20	22	2340	2510	5.3	1.4					31.0*	19500		
		C_2	C_2			0.42	2.9	100		20	22	2340		5.3						34.0	16000*		
2012	Marinković et al. [89]	C_1				0.60	4.3	0		32	20		2381							36.6			
		C_1				0.60	3.8	100		32	20	2264		2.0						33.6			
		C_1				0.52	3.6	0		32	20		2389							41.8			
		C_1				0.52	3.2	100		32	25	2276		2.0						41.1			
		C_1				0.47	3.0	0		32	25		2387							48.6			
		C_1				0.47	2.7	100		32	25	2273		2.0						48.1			
2012	Pereira et al. [27]	S_2	C_2		C_2	0.60	3.0	0	37.3	12	20		2720		0.6			2394		39.5	34400		2.9
		S_2	C_2		C_2	0.59	3.2	10	37.3	12	20	2010	2720	10.9	0.6			2377		40.0	33700		2.9
		S_2	C_2		C_2	0.57	3.5	30	37.3	12	20	2010	2720	10.9	0.6			2362		38.6	32300		2.7
		S_2	C_2		C_2	0.54	3.8	50	37.3	12	20	2010	2720	10.9	0.6			2349		37.6	32300		2.6
		S_2	C_2		C_2	0.46	4.6	100	37.3	12	20	2010		10.9				2308		38.6	29900		2.5
		S_2	C_2		C_2	0.45	3.2	0	37.3	12	20		2720		0.6			2450		53.3	41300		3.7
		S_2	C_2		C_2	0.44	3.3	10	37.3	12	20	2010	2720	10.9	0.6			2430		53.7	40600		3.4
		S_2	C_2		C_2	0.42	3.7	30	37.3	12	20	2010	2720	10.9	0.6			2406		51.0	36000		3.3
		S_2	C_2		C_2	0.67	4.0	50	37.3	12	20	2010	2720	10.9	0.6			2388		47.8*	35000*		3.1
		S_2	C_2		C_2	0.68	4.8	100	37.3	12	20	2010		10.9				2369		45.1*	34200*		3.0
		S_2	C_2		C_2	0.67	3.3	0	37.3	12	20		2720		0.6			2475		65.2*	43900*		4.5*
		S_2	C_2		C_2	0.70	3.4	10	37.3	12	20	2010	2720	10.9	0.6			2454		64.6*	43900*		4.2*
		S_2	C_2		C_2	0.53	3.8	30	37.3	12	20	2010	2720	10.9	0.6			2445		65.4*	41900*		4.5
		S_2	C_2		C_2	0.53	4.1	50	37.3	12	20	2010	2720	10.9	0.6			2428		63.2*	40200*		3.7
		S_2	C_2		C_2	0.53	5.0	100	37.3	12	20	2010		10.9				2417		63.0*	39700*		3.4
2013	Barbudo et al. [90]	C_2	C_2			0.54	3.0	0	41.4	20	22		2581		1.2		24.8			49.8	38480		
		C_2	C_2			0.54	3.0	20	41.4	20	22	2451	2581	7.3	1.2	40	24.8			50.5	37550		
		C_2	C_2			0.54	3.0	50	41.4	20	22	2451	2581	7.3	1.2	40	24.8			48.1	36280		
		C_2	C_2			0.54	2.9	100	41.4	20	22	2451		7.3		40				45.2	31280		
		C_2	C_2			0.45	3.1	0	41.4	20	22		2581		1.2		24.8			59.7	41630		
		C_2	C_2			0.45	3.1	20	41.4	20	22	2451	2581	7.3	1.2	40	24.8			64.7	40100		
		C_2	C_2			0.45	3.1	50	41.4	20	22	2451	2581	7.3	1.2	40	24.8			55.0	37000		
		C_2	C_2			0.45	3.1	100	41.4	20	22	2451		7.3		40				53.9	32750		
		C_2	C_2			0.40	3.2	0	41.4	20	22		2581		1.2		24.8			78.7*	48800*		
		C_2	C_2			0.40	3.2	20	41.4	20	22	2451	2581	7.3	1.2	40	24.8			69.9*	45700*		
		C_2	C_2			0.40	3.2	50	41.4	20	22	2451	2581	7.3	1.2	40	24.8			63.8	41630		
		C_2	C_2			0.40	3.1	100	41.4	20	22	2451		7.3		40				62.8*	37440		
2013	Butler et al. [91]	C_1	C_1	B_2	C_1	0.48	4.1	0		10	20		2670		1.5		11.9	2388		38.9	32090	5.8	3.2
		C_1	C_1	B_2	C_1	0.48	3.5	100		10	20	2360		4.7		15.1		2316		38.6	29920	5.2	3.5
		C_1	C_1	B_2	C_1	0.39	3.1	100		10	20	2280		6.2		22.1		2256		38.1	27370	5.2	3.1
		C_1	C_1	B_2	C_1	0.29	2.6	100		10	20	2220		7.8		25		2270		39.3*	27770	5.2	3.3
		C_1	C_1	B_2	C_1	0.34	2.3	0		10	20		2670		1.5		11.9	2407		61.9	35380	5.2	4.4
		C_1	C_1	B_2	C_1	0.31	2.1	100		10	20	2360		4.7		15.1		2341		60.1	30250	5.8	3.8
		C_1	C_1	B_2	C_1	0.27	1.8	100		10	20	2280		6.2		22.1		2285		60.2	29140	5.0	3.7
		C_1	C_1	B_2	C_1	0.19	1.5	100		10	20	2220		7.8		25		2294		62.8*	28490	4.4*	3.7

(continued on next page)

Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens				Concrete mix properties			Properties of coarse aggregate									Physical properties of concrete		Mechanical properties of concrete			
		Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
2013	Chen et al. [92]	S_2				0.52	3.0	100		25	20	2490		4.9						37.6			
		S_2				0.52	3.0	100		25	20	2570		2.9						43.3			
		S_2				0.52	2.9	100		25	20	2440		5.6						42.6			
		S_2				0.52	2.9	100		25	32	2470		5.3						44.7			
		S_2				0.52	3.1	0		25	32		2710		0.83					44.3			
2013	Hou and Zheng [93]	S_1				0.58	3.2	0		32	16		2970		0.8					44.6			
		S_1				0.52	3.2	53		32	16	2720	2970	4.8	0.8					41.4			
		S_1				0.58	3.2	100		32	16	2720		4.8						40.7			
		S_1				0.52	3.2	54		32	25	2650	2970	4.6	0.8					38.3			
		S_1				0.58	3.2	100		32	25	2650		4.6						36.6			
		S_1				0.52	3.2	53		32	25	2880	2970	4.4	0.8					41.2			
		S_1				0.58	3.2	100		32	25	2880		4.4						40.3			
2013	Ismail and Ramli [94]	S_1				0.41	1.7	15		20	32	2330	2600	4.4	0.7			2378		50.8			
		S_1				0.41	1.7	30		20	32	2330	2600	4.4	0.7			2368		44.9			
		S_1				0.41	1.7	45		20	32	2330	2600	4.4	0.7			2369		44.6			
		S_1				0.41	1.7	60		20	32	2330	2600	4.4	0.7			2354		42.4			
		S_1				0.41	1.7	15		20	32	2370	2600	4.0	0.7			2393		54.0			
		S_1				0.41	1.7	30		20	32	2370	2600	4.0	0.7			2404		56.0			
		S_1				0.41	1.7	45		20	32	2370	2600	4.0	0.7			2435		54.4			
		S_1				0.41	1.7	60		20	32	2370	2600	4.0	0.7			2347		40.6			
		S_1				0.41	1.7	15		20	20	2390	2600	3.6	0.7			2383		55.2			
		S_1				0.41	1.7	30		20	20	2390	2600	3.6	0.7			2374		53.5			
		S_1				0.41	1.7	45		20	20	2390	2600	3.6	0.7			2365		56.9			
		S_1				0.41	1.7	60		20	20	2390	2600	3.6	0.7			2345		54.7			
		S_1				0.41	1.7	15		20	20	2320	2600	4.6	0.7			2388		50.5			
		S_1				0.41	1.7	30		20	20	2320	2600	4.6	0.7			2383		48.9			
		S_1				0.41	1.7	45		20	20	2320	2600	4.6	0.7			2380		45.8			
		S_1				0.41	1.7	60		20	20	2320	2600	4.6	0.7			2346		40.0			
		S_1				0.41	1.7	15		20	20	2390	2600	3.7	0.7			2379		54.4			
		S_1				0.41	1.7	30		20	20	2390	2600	3.7	0.7			2371		50.2			
		S_1				0.41	1.7	45		20	20	2390	2600	3.7	0.7			2372		49.5			
		S_1				0.41	1.7	60		20	20	2390	2600	3.7	0.7			2355		40.4			
		S_1				0.41	1.7	15		20	20	2390	2600	3.5	0.7			2376		45.0			
		S_1				0.41	1.7	30		20	20	2390	2600	3.5	0.7			2374		46.9			
		S_1				0.41	1.7	45		20	20	2390	2600	3.5	0.7			2378		51.4			
		S_1				0.41	1.7	60		20	20	2390	2600	3.5	0.7			2348		53.2			
		S_1				0.41	1.7	15		20	20	2380	2600	3.8	0.7			2380		55.3			
		S_1				0.41	1.7	30		20	20	2380	2600	3.8	0.7			2364		55.9			
		S_1				0.41	1.7	45		20	20	2380	2600	3.8	0.7			2366		52.6			
		S_1				0.41	1.7	60		20	20	2380	2600	3.8	0.7			2351		48.0			
		S_1				0.41	1.7	15		20	20	2380	2600	3.8	0.7			2384		49.1			
		S_1				0.41	1.7	30		20	20	2380	2600	3.8	0.7			2366		49.9			
		S_1				0.41	1.7	45		20	20	2380	2600	3.8	0.7			2356		50.3			
		S_1				0.41	1.7	60		20	20	2380	2600	3.8	0.7			2359		47.5			
		S_1				0.41	1.7	15		20	20	2400	2600	3.5	0.7			2388		43.2			
		S_1				0.41	1.7	30		20	20	2400	2600	3.5	0.7			2367		53.7			
		S_1				0.41	1.7	45		20	20	2400	2600	3.5	0.7			2363		50.0			
		S_1				0.41	1.7	60		20	20	2400	2600	3.5	0.7			2352		43.3			
		S_1				0.41	1.7	15		20	20	2370	2600	4.0	0.7			2383		52.9			
		S_1				0.41	1.7	30		20	20	2370	2600	4.0	0.7			2362		49.9			
		S_1				0.41	1.7	45		20	20	2370	2600	4.0	0.7			2358		53.7			
		S_1				0.41	1.7	60		20	20	2370	2600	4.0	0.7			2349		46.0			
2013	Manzi et al. [95]	C_1	C_1	B_1		0.48	5.1	0	36.0	25	20		2570		1.2				2380	41.3	31400	6.4	3.8
		C_1	C_1	B_1		0.48	5.0	27	36.0	25	20	2250	2570	7.0	1.2				2320	51.4	30300	5.8	3.2
		C_1	C_1	B_1		0.48	4.9	64	36.0	25	20	2250	2570	7.0	1.2				2200	45.6*	24900*	4.9*	3.0*
		C_1	C_1	B_1		0.48	5.0	37	36.0	25	20	2250	2570	7.0	1.2				2270	44.7	26900	4.8	4.1
		C_1	C_1	B_1		0.48	5.0	37	36.0	25	20	2250	2570	7.0	1.2				2300	41.9	30600	5.7	3.3
2013	Matias et al. [96]	C_2				0.50	2.4	100		25	32	2452		4.1				2267		51.0			
		C_2				0.50	2.4	100		25	32	2452		4.1				2237		49.0			
		C_2				0.50	2.4	100		25	32	2452		4.1				2239		48.0			
		C_2				0.50	2.6	0		25	32	2452	2652	4.1	0.8			2350		52.0			
		C_2				0.50	2.5	50		25	32	2452	2652	4.1	0.8			2300		51.0			
		C_2				0.50	2.5	50		25	32	2452	2652	4.1	0.8			2284		51.0			
		C_2				0.50	2.5	50		25	32	2452	2652	4.1	0.8			2296		51.0			
		C_2				0.50	2.5	25		25	32	2452	2652	4.1	0.8			2332		52.0			
		C_2				0.50	2.5	25		25	25	2452	2652	4.1	0.8			2340		50.0			
		C_2				0.50	2.5	25		25	25	2452	2652	4.1	0.8			2308		49.0			

Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens				Concrete mix properties			Properties of coarse aggregate									Physical properties of concrete		Mechanical properties of concrete			
		Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
2013	Sheen et al. [97]	C_1	C_1	B_1		0.38	2.0	0		25	38		2630		1.2					54.1	34500	7.7	
		C_1	C_1	B_1		0.28	2.0	100		25	38	2260		7.5						38.3*	26300	6.5	
		C_1	C_1	B_1		0.28	2.0	100		25	38	2260		7.5						32.9*	24300	5.9	
		C_1	C_1	B_1		0.23	2.0	100		25	38	2260		7.5						33.2*	23500*	5.5	
		C_1	C_1	B_1		0.46	2.4	0		25	38		2630		1.2					42.2	29000	7.1	
		C_1	C_1	B_1		0.34	2.4	100		25	38	2260		7.5						31.3*	22900	5.7	
		C_1	C_1	B_1		0.34	2.4	100		25	38	2260		7.5						28.4*	21600	5.3	
		C_1	C_1	B_1		0.28	2.4	100		25	38	2260		7.5						28.0*	21500*	5.1	
		C_1	C_1	B_1		0.58	3.1	0		25	25		2630		1.2					28.8	24800	5.9	
		C_1	C_1	B_1		0.43	3.1	100		25	25	2260		7.5						26.5	19300*	5.5	
		C_1	C_1	B_1		0.43	3.1	100		25	25	2260		7.5						23.3*	17100*	5.1	
		C_1	C_1	B_1		0.35	3.1	100		25	25	2260		7.5						21.6*	17200*	4.7	
		C_1	C_1	B_1		0.67	3.5	0		25	25		2630		1.2					23.6	22800	5.2	
		C_1	C_1	B_1		0.49	3.5	100		25	25	2260		7.5						21.6	16500*	5.3	
		C_1	C_1	B_1		0.49	3.5	100		25	25	2260		7.5						18.0*	16200*	4.8	
		C_1	C_1	B_1		0.40	3.5	100		25	25	2260		7.5						18.8*	15300*	4.5	
		C_1	C_1	B_1		0.80	4.2	0		25	25		2630		1.2					17.3*	18900	4.4	
		C_1	C_1	B_1		0.59	4.2	100		25	25	2260		7.5						16.1	15100*	5.2*	
		C_1	C_1	B_1		0.59	4.2	100		25	25	2260		7.5						13.4*	13800*	4.0	
		C_1	C_1	B_1		0.48	4.2	100		25	25	2260		7.5						13.9*	14100*	3.9	
2013	Thomas et al. [14]	C_2	C_2		C_2	0.60	3.6	0		20	20		2540		1.8		31.0			38.0	34500		2.8
		C_2	C_2		C_2	0.59	3.3	20		20	20	2320	2540	5.3	1.8	42	31.0			41.0	32500		2.8
		C_2	C_2		C_2	0.57	3.3	50		20	20	2320	2540	5.3	1.8	42	31.0			44.0	31000		3.1
		C_2	C_2		C_2	0.54	3.0	100		20	20	2320		5.3		42	31.0			45.0	30200		2.4
		C_2	C_2		C_2	0.46	2.6	0		20	20		2540		1.8	42				51.5	37500		3.3
		C_2	C_2		C_2	0.45	2.5	20		20	20	2320	2540	5.3	1.8		31.0			50.5	36000		3.5
		C_2	C_2		C_2	0.44	2.5	50		20	20	2320	2540	5.3	1.8	42	31.0			45.0	33000		2.7
		C_2	C_2		C_2	0.42	2.3	100		20	20	2320		5.3		42				56.0	31500		3.7
		C_2	C_2		C_2	0.67	3.6	0		20	19		2540		1.8		31.0			37.0	35000		2.7
		C_2	C_2		C_2	0.68	3.4	20		20	19	2320	2540	5.3	1.8	42	31.0			33.5	32500		2.5
		C_2	C_2		C_2	0.67	3.0	50		20	19	2320	2540	5.3	1.8	42	31.0			32.0	30800		2.5
		C_2	C_2		C_2	0.70	2.3	100		20	19	2320		5.3		42				32.0	27000		2.3
		C_2	C_2		C_2	0.53	2.7	0		20	19		2540		1.8		31.0			45.0	35000		3.2
		C_2	C_2		C_2	0.53	2.5	20		20	19	2320	2540	5.3	1.8	42	31.0			44.0	34000		2.8
		C_2	C_2		C_2	0.53	2.2	50		20	19	2320	2540	5.3	1.8	42	31.0			41.0	32500		2.6
		C_2	C_2		C_2	0.52	1.8	100		20	19	2320		5.3		42				41.5	30500		2.3
		C_2	C_2		C_2	0.51	3.1	0		20	20		2540		1.8		31.0			46.5	36500		2.9
		C_2	C_2		C_2	0.52	3.2	20		20	20	2320	2540	5.3	1.8	42	31.0			44.0	36000		2.8
		C_2	C_2		C_2	0.54	3.0	50		20	20	2320	2540	5.3	1.8	42	31.0			41.0	33500		2.7
		C_2	C_2		C_2	0.58	2.8	100		20	20	2320		5.3		42				33.5	32000		2.3
		C_2	C_2		C_2	0.42	2.7	0		20	20		2540		1.8		31.0			58.0	37500		3.4
		C_2	C_2		C_2	0.42	2.9	20		20	20	2320	2540	5.3	1.8	42	31.0			53.5	36000		3.1
		C_2	C_2		C_2	0.44	2.7	50		20	20	2320	2540	5.3	1.8	42	31.0			54.0	34000		3.9
		C_2	C_2		C_2	0.49	2.5	100		20	20	2320		5.3		42				40.0	28000		2.4
2013	Ulloa et al. [98]	C_2				0.42	2.6	50		20	19	2330	2590	6.1	1.2	34.6	29.1			41.6			
		C_2				0.51	2.3	100		20	19	2330		6.1		34.6				31.4			
		C_2				0.52	2.6	50		20	19	2330	2590	6.1	1.2	34.6	29.1			35.5			
		C_2				0.61	2.3	100		20	19	2330		6.1		34.6				26.0			
		C_2				0.44	2.6	50		20	19	2320	2590	5.8	1.2	32.2	29.1			44.6			
		C_2				0.51	2.3	100		20	19	2320		5.8		32.2				36.7			
		C_2				0.62	2.3	100		20	19	2320		5.8		32.2				29.5			
		C_2				0.41	2.8	20		20	19	2360	2590	3.9	1.2	30.8	29.1			46.1			
		C_2				0.42	2.6	50		20	20	2360	2590	3.9	1.2	30.8	29.1			45.1			
		C_2				0.45	2.3	100		20	20	2360		3.9		30.8				42.9			
		C_2				0.50	2.8	20		20	20	2360	2590	3.9	1.2	30.8	29.1			39.3			
		C_2				0.52	2.6	50		20	20	2360	2590	3.9	1.2	30.8	29.1			39.5			
		C_2				0.54	2.3	100		20	20	2360		3.9		30.8				37.7			
		C_2				0.42	2.8	20		20	20	2350	2590	4.5	1.2	28.5	29.1			48.1			
		C_2				0.43	2.6	50		20	20	2350	2590	4.5	1.2	28.5	29.1			41.0			
		C_2				0.40	2.3	100		20	20	2350		4.5		28.5				38.7			
		C_2				0.51	2.8	20		20	20	2350	2590	4.5	1.2	28.5	29.1			42.7			
		C_2				0.52	2.6	50		20	20	2350	2590	4.5	1.2	28.5	29.1			35.4			
		C_2				0.50	2.3	100		20	20	2350		4.5		28.5				31.4			
		C_2				0.42	2.8	20		20	20	2350	2590	4.7	1.2	30.1	29.1			48.5			
		C_2				0.42	2.6	50		20	20	2350	2590	4.7	1.2	30.1	29.1			45.4			
		C_2				0.43	2.3	100		20	20	2350		4.7		30.1				37.0			
		C_2				0.52	2.8	20		20	20	2350	2590	4.7	1.2	30.1	29.1			41.3			
		C_2				0.52	2.6	50		20	20	2350	2590	4.7	1.2	30.1	29.1			36.8			
		C_2				0.56	2.3	100		20	20	2350		4.7		30.1				31.2			

(*continued on next page*)

Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens				Concrete mix properties			Properties of coarse aggregate									Physical properties of concrete		Mechanical properties of concrete			
		Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (*RCA %*)	Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f_r) (MPa)	Splitting tensile strength (f_{st}) (MPa)
2013	Xiao et al. [99]	S_2	C_1			0.41	2.6	0		32	20		2820		0.4					47.2	33100		
		S_2	C_1			0.38	2.6	33		32	20	2578	2820	9.3	0.4					42.4	30940		
		S_2	C_1			0.36	2.6	53		32	20	2578	2820	9.3	0.4					45.7	31910		
		S_2	C_1			0.34	2.6	72		32	20	2578	2820	9.3	0.4					36.7*	29090*		
		S_2	C_1			0.31	2.6	100		32	20	2578		9.3						38.9*	26510		
2013	Younis and Pilakoutas [9]	S_1				0.47	3.8	0		20	25		2610		1.0					53.1			
		S_1				0.47	3.7	20		20	25	2336	2610	3.6	1.0					50.0			
		S_1				0.47	3.6	50		20	25	2315	2610	3.6	1.0					45.3			
		S_1				0.47	3.6	75		20	25	2295	2610	3.6	1.0					44.0*			
		S_1				0.47	3.5	100		20	25	2273		3.6						41.6			
2014	Andreu and Miren [100]	S_2	C_1	B_1	C_1	0.29	2.9	0		10	10		2680		2.1		24.8	2510		102.1	50410	6.5	5.1
		S_2	C_1	B_1	C_1	0.29	2.8	20	100.0	10	10	2470	2680	3.7	2.1	24	24.8	2500		108.0*	48540	7.4*	5.7
		S_2	C_1	B_1	C_1	0.29	2.8	50	100.0	10	10	2470	2680	3.7	2.1	24	24.8	2480		104.8*	47930	7.7*	5.6*
		S_2	C_1	B_1	C_1	0.29	2.7	100	100.0	10	10	2470		3.7		24		2430		108.5*	46100	6.8*	5.1*
		S_2	C_1	B_1	C_1	0.29	2.8	20	60.0	10	10	2390	2680	4.9	2.1	25.2	24.8	2440		102.5	47790	8.0*	6.3*
		S_2	C_1	B_1	C_1	0.29	2.7	50	60.0	10	10	2390	2680	4.9	2.1	25.2	24.8	2400		103.1*	44280	6.8	5.1
		S_2	C_1	B_1	C_1	0.29	2.6	100	60.0	10	10	2390		4.9		25.2		2340		100.8*	40090	6.3	5.9*
		S_2	C_1	B_1	C_1	0.29	2.8	20	40.0	10	10	2300	2680	5.9	2.1	24.3	24.8	2470		104.3	48290	6.7	5.3
		S_2	C_1	B_1	C_1	0.29	2.7	50	40.0	10	10	2300	2680	5.9	2.1	24.3	24.8	2430		96.8*	43040	6.8	6.2*
		S_2	C_1	B_1	C_1	0.29	2.5	100	40.0	10	10	2300		5.9		24.3		2390		91.2*	37150	6.5	4.2
2014	Beltrán et al. [101]	C_2		B_1	C_2	0.65	4.6	0		20	30		2680		1.53		20			18.0*		2.4*	2.1
		C_2		B_1	C_2	0.65	4.7	25		20	30	2380	2680	6.94	1.53	29	20			14.7*		2.1*	1.8
		C_2		B_1	C_2	0.65	4.8	50		20	30	2380	2680	6.94	1.53	29	20			14.6*		1.9*	2.0
		C_2		B_1	C_2	0.65	4.8	75		20	30	2380	2680	6.94	1.53	29	20			14.2*		1.9*	1.7*
		C_2		B_1	C_2	0.72	5.8	0		20	20		2680		1.53		20			30.8		2.3*	2.3
		C_2		B_1	C_2	0.72	5.9	20		20	20	2380	2680	6.94	1.53	29	20			26.8		2.7	2.5
		C_2		B_1	C_2	0.72	6.0	40		20	20	2380	2680	6.94	1.53	29	20			26.6		2.0*	2.1
		C_2		B_1	C_2	0.45	1.9	0		16	20		2680		1.53		20			66.9		3.8	4.3
		C_2		B_1	C_2	0.45	2.3	20		16	20	2380	2680	6.94	1.53	29	20			49.3		2.8*	3.3
		C_2		B_1	C_2	0.45	2.5	40		16	20	2380	2680	6.94	1.53	29	20			40.9		2.7*	2.8
2014	Beltrán et al. [102]	C_2	C_2	B_2		0.60	3.5	0		16	20		2680		1.9			2167	2390	42.0	27300	4.7	
		C_2	C_2	B_2		0.60	3.4	20		16	20	2380	2680	6.9	1.9			2098	2330	42.9	26200	4.7	
		C_2	C_2	B_2		0.60	3.4	50		16	20	2380	2680	6.9	1.9			2060	2290	42.5	25900	4.7	
		C_2	C_2	B_2		0.60	3.2	100		16	20	2380		6.9				1989	2240	40.9	25100	4.8	
		C_2	C_2	B_2		0.50	2.7	0		16	20		2680		1.9			2188	2370	50.2	30000	5.1	
		C_2	C_2	B_2		0.50	2.6	20		16	20	2380	2680	6.9	1.9			2136	2330	51.6	29900	5.1	
		C_2	C_2	B_2		0.50	2.5	50		16	20	2380	2680	6.9	1.9			2112	2320	51.6	27200	5.1	
		C_2	C_2	B_2		0.50	2.4	100		16	20	2380		6.9				1998	2240	50.3	26400	5.3	
2014	Çakır and Sofyanlı [103]	C_2			C_1	0.50	3.4	0		22	22		2670							46.7			3.3
		C_2			C_1	0.50	3.4	50		12	22	2380	2670							46.9			3.8
		C_2			C_1	0.50	3.4	50		22	22	2380	2670							46.4			3.7
		C_2			C_1	0.50	3.4	100		22	22	2380								48.6			3.4
2014	Carneiro et al. [104]	C_1	C_1	B_2	C_1	0.52	2.2	0		19	10		2810		0.4					29.9	31100	3.6	3.2
		C_1	C_1	B_2	C_1	0.49	2.1	25		19	10	2500	2810	6.6	0.4					32.6	32100	3.3*	3.2
2014	Dilbas et al. [3]	C_2	C_2		C_2	0.50	3.5	50		8	20	2330	2750	3.8	0.8	41.4	24.3		2478	33.0	23437		2.2
		C_2	C_2		C_2	0.50	3.2	50		8	20	2280		4.1					2038	29.1	22896		1.6*
2014	Duan and Poon [105]	S_1	C_1		C_1	0.68	3.8	0		20	20		2600		0.9					34.5	25100		2.6
		S_1	C_1		C_1	0.68	3.6	100		20	20	2450		3.1						35.0	20850		2.5
		S_1	C_1		C_1	0.68	3.4	100		20	20	2370		7.1						29.2	21900		2.4
		S_1	C_1		C_1	0.68	3.4	100		20	20	2360		7.8						27.7	20490		1.9
		S_1	C_1		C_1	0.51	3.3	0		20	20		2600		0.9					48.3	30680		3.2
		S_1	C_1		C_1	0.51	3.1	100		20	20	2450		3.1						47.6	28860		3.4
		S_1	C_1		C_1	0.51	3.0	100		20	20	2370		7.1						42.0	24460		2.6
		S_1	C_1		C_1	0.51	3.0	100		20	20	2360		7.8						42.9	26550		2.6
		S_1	C_1		C_1	0.44	2.5	0		20	20		2600		0.9					61.6	32360		3.8
		S_1	C_1		C_1	0.44	2.4	100		20	20	2450		3.1						60.0	29420		3.9
		S_1	C_1		C_1	0.44	2.3	100		20	20	2370		7.1						53.7	24610		3.7
		S_1	C_1		C_1	0.44	2.3	100		20	20	2360		7.8						53.2	28500		3.4
		S_1	C_1		C_1	0.34	2.2	0		20	20		2600		0.9					80.8	35430		4.3
		S_1	C_1		C_1	0.34	2.1	100		20	20	2450		3.1						78.2	34760		4.7
		S_1	C_1		C_1	0.34	2.0	100		20	20	2370		7.1						71.2	29520		4.1
		S_1	C_1		C_1	0.34	2.0	100		20	20	2360		7.8						65.4	30620		4.2

Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens				Concrete mix properties			Properties of coarse aggregate									Physical properties of concrete		Mechanical properties of concrete			
		Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
2014	Folino and Xargay [106]	C_1	C_1		C_1	0.50	3.1	0		19	19		2730		0.3				2420	36.5	31667		4.0
		C_1	C_1		C_1	0.50	3.0	30		19	19	2570	2730	2.7	0.3				2385	33.6	28617		3.9
		C_1	C_1		C_1	0.50	3.0	60		19	19	2570	2730	2.7	0.3				2382	30.4	24533		3.9
		C_1	C_1		C_1	0.50	2.8	100		19	19	2570		2.7					2346	29.1	20750		3.3
2014	Gayarre et al. [107]	C_2				0.65	3.1	0		20	19		2500		1.7		32.0		2370	40.5			
		C_2				0.65	3.2	20		20	19	2300	2500	5.2	1.7	40.2	32.0		2340	39.5			
		C_2				0.65	3.2	50		20	19	2300	2500	5.2	1.7	40.2			2330	40.8			
		C_2				0.65	3.2	100		20	19	2300		5.2		40.2	32.0		2320	43.7*			
		C_2				0.65	3.1	0		20	19		2500		1.7		32.0		2370	40.5			
		C_2				0.65	3.1	20		20	19	2300	2500	5.5	1.7	28.6	32.0		2360	41.0			
		C_2				0.65	3.1	50		20	19	2300	2500	5.5	1.7	28.6	32.0		2350	38.8			
		C_2				0.65	3.2	100		20	19	2300		5.5		28.6			2350	39.9*			
2014	Kang et al. [108]	C_1	C_1	B_2	C_1	0.42	2.7	0		25	25		2570		1.1					38.6	29200	10.2*	3.3
		C_1	C_1	B_2	C_1	0.40	2.7	16		25	25	2200	2570	5.4	1.1					32.7*	29200	9.7*	3.0
		C_1	C_1	B_2	C_1	0.39	2.2	37		25	25	2200	2570	5.4	1.1					31.7*	26500	9.0*	2.7
		C_1	C_1	B_2	C_1	0.36	2.7	52		25	20	2200	2570	5.4	1.1					29.0*	25300	8.9*	2.7
2014	Pedro et al. [109]	S_1	C_2		C_2	0.86	4.6	0		22	20		2537		1.3					23.9	33300*		2.8
		S_1	C_2		C_2	0.65	3.4	0		22	20		2537		1.3					38.7	36700		3.2
		S_1	C_2		C_2	0.41	2.9	0		22	20		2537		1.3					71.1	46900		5.2
		S_1	C_2		C_2	0.87	4.6	100		22	20	2451		7.8						19.7	25200		2.0
		S_1	C_2		C_2	0.66	3.4	100		22	20	2387		6.9						35.7	29500		2.9
		S_1	C_2		C_2	0.42	2.8	100		22	20	2362		4.2						66.8	40300*		4.6*
		S_1	C_2		C_2	0.86	4.6	100		22	20	2456		7.5						21.8	26500		2.0
		S_1	C_2		C_2	0.65	3.5	100		22	20	2455		6.4						36.1	30000		2.9
		S_1	C_2		C_2	0.42	2.9	100		22	20	2496		4.2						68.5	40300*		4.8*
		S_1	C_2		C_2	0.81	4.9	0		22	20		2665		1.0					27.5	34700*		2.9
		S_1	C_2		C_2	0.63	3.6	0		22	20		2665		1.0					42.4	38300		3.3
		S_1	C_2		C_2	0.40	3.0	0		22	20		2665		1.0					72.3	47600		5.5*
		S_1	C_2		C_2	0.84	4.5	100		22	20	2401		7.6						21.0	25900		2.1
		S_1	C_2		C_2	0.63	3.5	100		22	20	2484		5.4						41.1	31200		3.0
		S_1	C_2		C_2	0.40	2.8	100		22	20	2363		3.6						70.2	40400*		4.9*
		S_1	C_2		C_2	0.82	4.7	100		22	20	2447		6.9						23.6	27800*		2.2
		S_1	C_2		C_2	0.64	3.4	100		22	22	2458		5.8						39.7	31500*		3.0
		S_1	C_2		C_2	0.42	2.9	100		22	22	2464		3.9						66.5	40200*		5.0*
2014	Pepe et al. [110]	C_1	C_1		C_1	0.64	3.0	0		19	20		2634		1.3					33.0	24770		3.9
		C_1	C_1		C_1	0.77	3.1	100		19	20	2268		4.9						27.5	24860		3.4*
		C_1	C_1		C_1	0.70	3.4	100		19	20	1946		11.9						29.9	24400		3.7*
2014	Thomas et al. [111]	C_1	C_1		C_1	0.60	3.6	0		19	19		2730		0.5		23.0		2410	47.8	34200		4.0
		C_1	C_1		C_1	0.59	3.3	20		19	19	2320	2730	5.3	0.5	37	23.0		2400	49.3	32300		4.1
		C_1	C_1		C_1	0.57	3.3	50		19	19	2320	2730	5.3	0.5	37	23.0		2380	47.5	30500		4.7*
		C_1	C_1		C_1	0.54	3.0	100		19	19	2320		5.3		37			2380	53.7*	30100		4.9*
		C_1	C_1		C_1	0.46	2.6	0		19	19		2730		0.5		23.0		2480	62.0	37400		4.6
		C_1	C_1		C_1	0.45	2.5	20		19	19	2320	2730	5.3	0.5	37	23.0		2450	64.8	36100		4.7
		C_1	C_1		C_1	0.44	2.5	50		19	19	2320	2730	5.3	0.5	37	23.0		2450	63.5*	34000		4.8*
		C_1	C_1		C_1	0.42	2.3	100		19	19	2320		5.3		37			2430	65.1*	31400		5.0*
		C_1	C_1		C_1	0.67	3.6	0		19	19		2730		0.5		23.0		2380	62.0*	34900		2.7
		C_1	C_1		C_1	0.68	3.4	20		19	19	2320	2730	5.3	0.5	37	23.0		2350	64.8*	32200		2.5
		C_1	C_1		C_1	0.67	3.0	50		19	19	2320	2730	5.3	0.5	37	23.0		2340	63.5*	30100		2.4
		C_1	C_1		C_1	0.70	2.3	100		19	19	2320		5.3		37			2300	65.1*	26800		2.3
		C_1	C_1		C_1	0.53	2.7	0		19	19		2730		0.5		23.0		2430	57.3	34900		3.7
		C_1	C_1		C_1	0.53	2.5	20		19	19	2320	2730	5.3	0.5	37	23.0		2410	54.9	33800		3.2
		C_1	C_1		C_1	0.53	2.2	50		19	19	2320	2730	5.3	0.5	37	23.0		2400	51.5*	32700		2.7
		C_1	C_1		C_1	0.52	1.8	100		19	19	2320		5.3		37			2370	50.3	30200		2.4
		C_1	C_1		C_1	0.51	3.1	0		19	19		2730		0.5		23.0		2430	60.1	36300		3.3
		C_1	C_1		C_1	0.52	3.2	20		19	19	2320	2730	5.3	0.5	37	23.0		2420	56.5	35500		2.9
		C_1	C_1		C_1	0.54	3.0	50		19	19	2320	2730	5.3	0.5	37	23.0		2400	48.9	33400		2.6
		C_1	C_1		C_1	0.58	2.8	100		19	19	2320		5.3		37			2340	43.1	31500		2.4
		C_1	C_1		C_1	0.42	2.7	0		19	19		2730		0.5		23.0		2490	72.9	38700		4.1
		C_1	C_1		C_1	0.42	2.9	20		19	19	2320	2730	5.3	0.5	37	23.0		2460	67.4	35900		3.5
		C_1	C_1		C_1	0.44	2.7	50		19	19	2320	2730	5.3	0.5	37	23.0		2400	61.2	32900		2.9
		C_1	C_1		C_1	0.49	2.5	100		19	19	2320		5.3		37			2390	53.7	28400		2.5

(*continued on next page*)

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Table A1 (*continued*)

Year of publication	Source	Geometric properties of specimens				Concrete mix properties			Properties of coarse aggregate									Physical properties of concrete		Mechanical properties of concrete			
		Compressive strength tests	Elastic modulus tests	Flexural strength tests	Splitting tensile strength tests	Effective water-to-cement ratio (w_{eff}/c)	Aggregate-to-cement ratio (a/c)	RCA replacement ratio (RCA %)	Parent concrete strength (MPa)	Nominal maximum RCA size (mm)	Nominal maximum NA size (mm)	Bulk density of RCA (kg/m^3)	Bulk density of NA (kg/m^3)	Water absorption of RCA (WA_{RCA}) (%)	Water absorption of NA (WA_{NA}) (%)	Los Angeles abrasion of RCA (LA_{RCA})	Los Angeles abrasion of NA (LA_{NA})	Density of hardened concrete AD (ρ_{ad}) (kg/m^3)	Density of hardened concrete SSD (ρ_{SSD}) (kg/m^3)	Compressive strength (f'_c) (MPa)	Elastic modulus (E_c) (MPa)	Flexural strength (f'_r) (MPa)	Splitting tensile strength (f'_{st}) (MPa)
2014	Wardeh et al. [28]	S_1	C_1	B_1	C_1	0.50	2.9	0		20	20			6.5						37.0	39500	4.9	3.5
		S_1	C_1	B_1	C_1	0.50	2.5	30		20	20	2240		6.5						33.0	36000	4.7	3.2
		S_1	C_1	B_1	C_1	0.50	1.4	65		20	20	2240		6.5						39.5*	33500*	4.4*	3.2*
		S_1	C_1	B_1	C_1	0.50	1.2	100		20	20	2240								39.0	30500	4.0	3.0
2014	Capitanio et al. [112]	C_1	C_1	B_1	C_2	0.55	2.8	0		12	12		2710		2.0				2347	40.9	29300	5.1	3.2
		C_1	C_1	B_1	C_2	0.53	2.6	25		12	12	2220	2710	6.1	2.0				2289	41.0	29000	4.7	2.6
		C_1	C_1	B_1	C_2	0.51	2.5	50		12	12	2220	2710	6.1	2.0				2236	40.5	28200	4.6	2.6
		C_1	C_1	B_1	C_2	0.47	2.1	100		12	12	2220		6.1					2199	40.3	27200	3.7	2.4
		C_1	C_1	B_1	C_2	0.47	2.1	100		7	7	2220			2.0				2138	38.0	26700	3.4	2.3
		C_1	C_1	B_1	C_2	0.53	2.7	0		7	7		2570	4.1	2.0				2287	40.1	28100	5.3	3.3
		C_1	C_1	B_1	C_2	0.49	2.4	50		7	7	2150	2570	4.1	2.0				2174	41.2	27900	5.0	3.0
		C_1	C_1	B_1	C_2	0.45	2.1	100		7	7	2150	2570	4.1	2.0				2147	40.8	25700	3.9	2.5
		C_1	C_1	B_1	C_2	0.45	2.1	100		7	7	2150		4.1					2115	39.2	25100	3.6	2.4

C_1 = 100 × 200 mm cylinders; C_2 = 150 × 300 mm cylinders; S_1 = 100 mm cubes; S_2 = 150 mm cubes; B_1 = 100 × 100 × 500 mm beam specimens; B_2 = 150 × 150 × 750 mm beam specimens.
*Datasets that deviated significantly from the global trend-lines of the database (i.e. ±50%)

References

[1] F.P. Torgal, S. Jalali, Construction and Demolition (C & D) Wastes, Eco-efficient Construction and Building Materials, Springer, London, 2011, pp. 51–73.
[2] M. Behera, S.K. Bhattacharyya, A.K. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete–A breakthrough towards sustainability in construction sector: A review, Constr. Build. Mater. 68 (2014) 501–516.
[3] H. Dilbas, M. Şimşek, Ö. Çakır, An investigation on mechanical and physical properties of recycled aggregate concrete (RAC) with and without silica fume, Constr. Build. Mater. 61 (2014) 50–59.
[4] P.K. Mehta, H. Meryman, Tools for reducing carbon emissions due to cement consumption, Struct. Magaz. 1 (1) (2009) 11–15.
[5] F.P. Torgal, Y. Ding, S. Miraldo, Z. Abdollahnejad, J.A. Labrincha, Are geopolymers moere suitable than portland cement to produce high volume recycled aggregates HPC, Constr. Build. Mater. 36 (2012) 1048–1052.
[6] S.C. Kou, C.S. Poon, H.W. Wan, Properties of concrete prepared with low-grade recycled aggregates, Constr. Build. Mater. 36 (2012) 881–889.
[7] I.B. Topcu, S. Şengel, Properties of concretes produced with waste concrete aggregate, Cem. Concr. Res. 34 (8) (2004) 1307–1312.
[8] Ö. Çakır, Experimental analysis of properties of recycled coarse aggregate (RCA) concrete with mineral additives, Constr. Build. Mater. 68 (2014) 17–25.
[9] K.H. Younis, K. Pilakoutas, Strength prediction model and methods for improving recycled aggregate concrete, Constr. Build. Mater. 49 (2013) 688–701.
[10] J.Z. Xiao, J.B. Li, C. Zhang, On relationships between the mechanical properties of recycled aggregate concrete: an overview, Mater. Struct. 39 (6) (2006) 655–664.
[11] R. Sriravindrarajah, N.D.H. Wang, L.J.W. Ervin, Mix Design for Pervious Recycled Aggregate Concrete. International, J. Concr. Struct. Mater. 6 (4) (2012) 239–246.
[12] P.S. Lovato, E. Possan, D.C.C. Dal Molin, Â.B. Masuero, J.L.D. Ribeiro, Modeling of mechanical properties and durability of recycled aggregate concretes, Constr. Build. Mater. 26 (1) (2012) 437–447.
[13] P. Pereira, L. Evangelista, Brito.J. De, The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates, Constr. Build. Mater. 28 (1) (2012) 722–729.
[14] C. Thomas, J. Setién, J.A. Polanco, P. Alaejos, M.S. de Juan, Durability of recycled aggregate concrete, Constr. Build. Mater. 40 (2013) 1054–1065.
[15] M. Harada, T. Soshiroda, S. Kubota, T. Ikeda, Y. Kasai, Strength and elastic modulus of recycled aggregate concrete, In: Proceedings of the Second International RILEM Symposium on Demolition and Reuse of Concrete and Masonry, 1988, vol. 2, pp. 565-574.
[16] R.S. Ravindrarajah, C.T. Tam, Properties of concrete made with crushed concrete as coarse aggregate, Magaz. Concr. Res. 37 (130) (1985) 29–38.
[17] N.K. Bairagi, K. Ravande, V.K. Pareek, Behaviour of concrete with different proportions of natural and recycled aggregates, Resour. Conserv. Recycl. 9 (1) (1993) 109–126.
[18] M.B. de Oliveira, E. Vazquez, The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete, Waste Manage. 16 (1) (1996) 113–117.
[19] R. Dillmann. Concrete with recycled concrete aggregate, in: Sustainable Construction: Use of Recycled Concrete Aggregate-Producings of The International Symposium Held at Department of Trade and Industry Conference Centre, London, UK, 1998, pp. 11–12.
[20] R.K. Dhir, Sustainability of Recycled Concrete Aggregate for Use IN BS 5328 Designated Mixes, Proc. ICE-Struct. Build. 134 (3) (1999) 257–274.
[21] M. Tavakoli, P. Soroushian, Strengths of recycled aggregate concrete made using field-demolished concrete as aggregate, ACI Mater. J. 93 (2) (1996) 182–190.
[22] K. Zilch, F. Roos, An equation to estimate the modulus of elasticity of concrete with recycled aggregates, Civ. Eng. 76 (4) (2001) 187–191.
[23] G.F. Kheder, S.A. Al-Windawi, Variation in mechanical properties of natural and recycled aggregate concrete as related to the strength of their binding mortar, Mater. Struct. 38 (7) (2005) 701–709.
[24] K. Rahal, Mechanical properties of concrete with recycled coarse aggregate, Build. Environ. 42 (1) (2007) 407–415.
[25] V. Corinaldesi, Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates, Constr. Build. Mater. 24 (9) (2010) 1616–1620.
[26] C. Hoffmann, S. Schubert, A. Leemann, M. Motavalli, Recycled concrete and mixed rubble as aggregates: influence of variations in composition on the concrete properties and their use as structural material, Constr. Build. Mater. 35 (2012) 701–709.
[27] P. Pereira, L. Evangelista, J. de Brito, The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates, Cement Concr. Compos. 34 (9) (2012) 1044–1052.
[28] G. Wardeh, E. Ghorbel, H. Gomart, Mix design and properties of recycled aggregate concretes: applicability of eurocode 2, Int. J. Concr. Struct. Mater. (2014) 1–20.
[29] J. Xiao, P. Li, W. Qin, Study on bond-slip between recycled concrete and rebars, J. Tongji Univ. 34 (1) (2006) 13.
[30] D.X. Xuan, L.J.M. Houben, A.A.A. Molenaar, Z.H. Shui, Mechanical properties of cement-treated aggregate material–a review, Mater. Des. 33 (2012) 496–502.

[31] I. Mansouri, T. Ozbakkaloglu, O. Kisi, T. Xie, Predicting Behavior of FRP-Confined Concrete using Neuro Fuzzy, Neural Network, Multivariate Adaptive Regression Splines and M5 Model Tree Techniques, Mater. Struct. (2016), http://dx.doi.org/10.1617/s11527-015-0790-4.
[32] I. Mansouri, A. Gholampour, O. Kisi, T. Ozbakkaloglu, Evaluation of peak and residual conditions of actively confined concrete using neuro-fuzzy and neural computing techniques, Neural Comput. Appl. (2016), http://dx.doi.org/10.1007/s00521-016-2492-4.
[33] J.C. Lim, M. Karakus, T. Ozbakkaloglu, Evaluation of ultimate conditions of FRP-confined concrete columns using genetic programming, Comput. Struct. 162 (2016) 28–37.
[34] M. Jalal, A.A. Ramezanianpour, A.R. Pouladkhan, P. Tedro, Application of genetic programming (GP) and ANFIS for strength enhancement modeling of CFRP-retrofitted concrete cylinders, Neural Comput. Appl. 23 (2013) 455–470.
[35] M.A. Mashrei, R. Seracino, M.S. Rahman, Application of artificial neural networks to predict the bond strength of FRP-to-concrete joints, Constr. Build. Mater. 40 (2013) 812–821.
[36] A. Sadrmomtazi, J. Sobhani, M.A. Mirgozar, Modeling compressive strength of EPS lightweight concrete using regression, neural network and ANFIS, Constr. Build. Mater. 42 (2013) 205–216.
[37] R. Perera, D. Tarazona, A. Ruiz, A. Martín, Application of artificial intelligence techniques to predict the performance of RC beams shear strengthened with NSM FRP rods. Formulation of design equations, Compos. B Eng. 66 (2014) 162–173.
[38] T.M. Pham, M.N. Hadi, Predicting stress and strain of frp-confined square/rectangular columns using artificial neural networks, J. Compos. Constr. 18 (6) (2014) 1–9. 04014019-1-9.
[39] H. Mashhadban, S.S. Kutanaei, M.A. Sayarinejad, Prediction and modeling of mechanical properties in fiber reinforced self-compacting concrete using particle swarm optimization algorithm and artificial neural network, Constr. Build. Mater. 119 (2016) 277–287.
[40] Z.H. Duan, S.C. Kou, C.S. Poon, Prediction of compressive strength of recycled aggregate concrete using artificial neural networks, Constr. Build. Mater. 40 (2013) 1200–1206.
[41] K. Sahoo, P. Sarkar, R. Davis, Artificial neural networks for prediction of compressive strength of recycled aggregate concrete, Int. J. Chem. Metal. Civ. Eng. 3 (1) (2016) 81–85.
[42] N. Deshpande, S. Londhe, S. Kulkarni, Modeling compressive strength of recycled aggregate concrete by artificial neural network, model tree and non-linear regression, Int. J. Sustain. Build Environ. 3 (2014) 187–198.
[43] Z.H. Duan, S.C. Kou, C.S. Poon, Using artificial neural networks for predicting the elastic modulus of recycled aggregate concrete, Constr. Build. Mater. 44 (2013) 524–532.
[44] A. Behnood, J. Olek, M.A. Glinicki, Predicting modulus elasticity of recycled aggregate concrete using M5' model tree algorithm, Constr. Build. Mater. 94 (2015) 137–147.
[45] I. Gonzalez-Taboada, B. Gonzalez-Fonteboa, F. Martinez-Abella, J. Perez-Ordonez, Prediction of the mechanical properties of structural recycled concrete using multivariable regression and genetic programming, Constr. Build. Mater. 106 (2016) 480–499.
[46] A.H. Alavi, A.H. Gandomi, A robust data mining approach for formulation of geotechnical engineering systems, Eng. Comput. 28 (3) (2011) 242–274.
[47] A.H. Gandomi, D.A. Roke, Assessment of artificial neural network and genetic programming as predictive tools, Adv. Eng. Softw. 88 (2015) 63–72.
[48] A.H. Gandomi, S. Babanajad, A. Alavi, Y. Farnam, Novel approach to strength modeling of concrete under triaxial compression, J. Mater. Civ. Eng. (2012), http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000494, 1132-1143.
[49] C. Ferreira, Gene expression programming: a new adaptive algorithm for solving problems, Complex Syst. 13 (2) (2001) 87–129.
[50] A.H. Gandomi, A.H. Alavi, M.R. Mirzahosseini, F.M. Nejad, Nonlinear genetic-based models for prediction of flow number of asphalt mixtures, J. Mater. Civ. Eng. 23 (3) (2011) 248–263.
[51] P.K. Muduli, S.K. Das, Evaluation of liquefaction potential of soil based on standard penetration test using multi-gene genetic programming model, Acta Geophys. 62 (3) (2014) 529–543.
[52] K. Yoda, T. Yoshikane, Y. Nakashima, T. Soshiroda, Recycled cement and recycled concrete in Japan. In: Proceedings of the International Conference on Demolition and Reuse of Concrete and Masonry, 1988, pp. 527-536.
[53] M.C. Limbachiya, T. Leelawat, R.K. Dhir, Use of recycled concrete aggregate in high-strength concrete, Mater. Struct. 33 (9) (2000) 574–580.
[54] A. Ajdukiewicz, A. Kliszczewicz, Influence of recycled aggregates on mechanical properties of HS/HPC, Cem. Concr. Compos. 24 (2) (2002) 269–279.
[55] J. Gómez-Soberón, Porosity of recycled concrete with substitution of recycled concrete aggregate: an experimental study, Cem. Concr. Res. 32 (8) (2002) 1301–1311.
[56] A. Gonçalves, A. Esteves, M. Vieira, Influence of recycled concrete aggregates on concrete durability, In: International RILEM Conference on the Use of Recycled Materials in Buildings and Structures, 2004, pp. 554–562.
[57] C.S. Poon, Z.H. Shui, L. Lam, H. Fok, S.C. Kou, Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete, Cem. Concr. Res. 34 (1) (2004) 31–36.
[58] Y.H. Lin, Y.Y. Tyan, T.P. Chang, C.Y. Chang, An assessment of optimal mixture for concrete made with recycled concrete aggregates, Cem. Concr. Res. 34 (8) (2004) 1373–1380.
[59] X. Wei, Experimental study on influence of recycled coarse aggregates contents on properties of recycled aggregate concrete, Concrete 9 (2006) 13.
[60] M. Etxeberria, A.R. Mari, E. Vazquez, Recycled aggregate concrete as structural material, Mater. Struct. 40 (5) (2007) 529–541.
[61] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cem. Concr. Res. 37 (5) (2007) 735–742.
[62] L. Evangelista, J. De Brito, Mechanical behaviour of concrete made with fine recycled concrete aggregates, Cem. Concr. Compos. 29 (5) (2007) 397–401.
[63] C.S. Poon, S.C. Kou, L. Lam, Influence of recycled aggregate on slump and bleeding of fresh concrete, Mater. Struct. 40 (9) (2007) 981–988.
[64] A.B. Ajdukiewicz, A.T. Kliszczewicz, Comparative tests of beams and columns made of recycled aggregate concrete and natural aggregate concrete, J. Adv. Concr. Technol. 5 (2) (2007) 259–273.
[65] M.P. Hu, Mechanical properties of concrete prepared with different recycled coarse aggregates replacement rate, Chin. Concr. J. 2 (2007) 52–54.
[66] S.C. Kou, C.S. Poon, D. Chan, Influence of fly ash as cement replacement on the properties of recycled aggregate concrete, J. Mate. Civ. Eng. 19 (9) (2007) 709–717.
[67] Z.W. Wang, Production and properties of high quality recycled aggregates, Concrete 3 (2007) 74–77.
[68] M. Casuccio, M.C. Torrijos, G. Giaccio, R. Zerbino, Failure mechanism of recycled aggregate concrete, Constr. Build. Mater. 22 (7) (2008) 1500–1506.
[69] M.P. Hu, Mechanical properties of recycled aggregate concrete at early ages, Concrete 5 (2008) 37–41.
[70] S.C. Kou, C.S. Poon, D. Chan, Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete, Mater. Struct. 41 (7) (2008) 1191–1201.
[71] K.H. Yang, H.S. Chung, A.F. Ashour, Influence of type and replacement level of recycled aggregates on concrete properties, ACI Mater. J. 105 (3) (2008).
[72] H. Zhou, B.K. Liu, L.U. Guo, Experimental research on the basic mechanical properties of recycled aggregate concrete, J. Anhui Inst. Arch. Ind. 6 (2008) 3.
[73] A. Domingo-Cabo, C. Lázaro, F. López-Gayarre, M.A. Serrano-López, P. Serna, J. O. Castaño-Tabares, Creep and shrinkage of recycled aggregate concrete, Constr. Build. Mater. 23 (7) (2009) 2545–2553.
[74] A.K. Padmini, K. Ramamurthy, M.S. Mathews, Influence of parent concrete on the properties of recycled aggregate concrete, Constr. Build. Mater. 23 (2) (2009) 829–836.
[75] X. Yang, J. Wu, J.G. Liang, Experimental study on relationship between tensile strength and compressive strength of recycled aggregate concrete, Sichuan Build. Sci. 35 (2009) 190–192.
[76] H. Ye, Experimental study on mechanical properties of concrete made with high quality recycled aggregate, Sichuan Build. Sci. 35 (2009) 195–199.
[77] R. Kumutha, K. Vijai, Strength of concrete incorporating aggregates recycled from demolition waste, ARPN J. Eng. Appl. Sci. 5 (5) (2010) 64–71.
[78] V. Radonjanin, M. Malešev, S. Marinković, Recycled concrete as aggregate for structural concrete production, Sustain 2 (5) (2010) 1204–1225.
[79] C.J. Zega, Maio.A.A. Di, Recycled concretes made with waste ready-mix concrete as coarse aggregate, J. Mater. Civ. Eng. 23 (3) (2010) 281–286.
[80] G.F. Belén, M.A. Fernando, C.L. Diego, S.P. Sindy, Stress–strain relationship in axial compression for concrete using recycled saturated coarse aggregate, Constr. Build. Mater. 25 (5) (2011) 2335–2342.
[81] G. Fathifazl, A.G. Razaqpur, O.B. Isgor, A. Abbas, B. Fournier, S. Foo, Creep and drying shrinkage characteristics of concrete produced with coarse recycled concrete aggregate, Cem. Concr. Compos. 33 (10) (2011) 1026–1037.
[82] B. González-Fonteboa, F. Martínez-Abella, J. Eiras-López, S. Seara-Paz, Effect of recycled coarse aggregate on damage of recycled concrete, Mater. Struct. 44(10): 1759–1771.
[83] M.C. Rao, S.K. Bhattacharyya, S.V. Barai, Influence of field recycled coarse aggregate on properties of concrete, Mater. Struct. 44 (1) (2011) 205–220.
[84] R. Somna, C. Jaturapitakkul, W. Chalee, P. Rattanachu, Effect of the water to binder ratio and ground fly ash on properties of recycled aggregate concrete, J. Mater. Civ. Eng. 24 (1) (2011) 16–22.
[85] A. Abd Elhakam, A.E. Mohamed, E. Awad, Influence of self-healing, mixing method and adding silica fume on mechanical properties of recycled aggregates concrete, Constr. Build. Mater. 35 (2012) 421–427.
[86] Z.L. Cui, S.S. Lu, Z.S. Wang, Influence of Recycled Aggregate on Strength and Anti-carbonation Properties of Recycled Aggregate Concrete, J. Build. Mater. 15 (2) (2012) 264–267.
[87] H. Li, J.Z. Xiao, On Fatigue Strength of Recycled Aggregate concrete Based on Its Elastic Modulus, J. Build. Mater. 15 (2) (2012) 260–263.
[88] M. Limbachiya, M.S. Meddah, Y. Ouchagour, Performance of Portland/silica fume cement concrete produced with recycled concrete aggregate, ACI Mater. J. 109 (1) (2012).
[89] S. Marinković, V. Radonjanin, M. Malešev, I. Gnjatović, Comparative environmental assessment of natural and recycled aggregate concrete, Waste Manage. 30 (11) (2010) 2255–2264.
[90] A. Barbudo, J. de Brito, L. Evangelista, M. Bravo, F. Agrela, Influence of water-reducing admixtures on the mechanical performance of recycled concrete, J. Clean Prod. 59 (2013) 93–98.
[91] L. Butler, J.S. West, S.L. Tighe, Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength, Constr. Build. Mater. 47 (2013) 1292–1301.
[92] Z.P. Chen, J.J. Xu, H.H. Zheng, Y.S. Su, J.Y. Xue, J.T. Li, Basic mechanical properties test and stress-strain constitutive relations of recycled coarse aggregate concrete, J. Build Mater. 16 (1) (2013) 24–32.

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[93] Y.L. Hou, G. Zheng, Mechanical properties of recycled aggregate concrete in different age, J. Build Mater. 16 (4) (2013) 683–687.
[94] S. Ismail, M. Ramli, Engineering properties of treated recycled concrete aggregate (RCA) for structural applications, Constr. Build. Mater. 44 (2013) 464–476.
[95] S. Manzi, C. Mazzotti, M.C. Bignozzi, Short and long-term behavior of structural concrete with recycled concrete aggregate, Cem. Concr. Compos. 37 (2013) 312–318.
[96] D. Matias, J. de Brito, A. Rosa, D. Pedro, Mechanical properties of concrete produced with recycled coarse aggregates–influence of the use of superplasticizers, Constr. Build. Mater. 44 (2013) 101–109.
[97] Y.N. Sheen, H.Y. Wang, Y.P. Juang, D.H. Le, Assessment on the engineering properties of ready-mixed concrete using recycled aggregates, Constr. Build. Mater. 45 (2013) 298–305.
[98] V.A. Ulloa, E. García-Taengua, M.J. Pelufo, A. Domingo, P. Serna, New views on effect of recycled aggregates on concrete compressive strength, ACI Mater. J. 110 (6) (2013).
[99] J. Xiao, H. Li, Z. Yang, Fatigue behavior of recycled aggregate concrete under compression and bending cyclic loadings, Constr. Build. Mater. 38 (2013) 681–688.
[100] G. Andreu, E. Miren, Experimental analysis of properties of high performance recycled aggregate concrete, Constr. Build. Mater. 52 (2014) 227–235.
[101] M.G. Beltrán, F. Agrela, A. Barbudo, J. Ayuso, A. Ramírez, Mechanical and durability properties of concretes manufactured with biomass bottom ash and recycled coarse aggregates, Constr. Build. Mater. 72 (2014) 231–238.
[102] M.G. Beltrán, A. Barbudo, F. Agrela, A.P. Galvín, J.R. Jiménez, Effect of cement addition on the properties of recycled concretes to reach control concretes strengths, J. Clean Prod. 79 (2014) 124–133.
[103] Ö. Çakır, Ö.Ö. Sofyanlı, Influence of silica fume on mechanical and physical properties of recycled aggregate concrete, HBRC J. 11 (2) (2015) 157–166.
[104] J.A. Carneiro, P.R.L. Lima, M.B. Leite, R.D. Toledo Filho, Compressive stress–strain behavior of steel fiber reinforced-recycled aggregate concrete, Cem. Concr. Compos. 46 (2014) 65–72.
[105] Z.H. Duan, C.S. Poon, Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars, Mater. Des. 58 (2014) 19–29.
[106] P. Folino, H. Xargay, Recycled aggregate concrete–mechanical behavior under uniaxial and triaxial compression, Constr. Build. Mater. 56 (2014) 21–31.
[107] F.L. Gayarre, C.L.C. Pérez, M.A.S. López, A.D. Cabo, The effect of curing conditions on the compressive strength of recycled aggregate concrete, Constr. Build. Mater. 53 (2014) 260–266.
[108] T.H.K. Kang, W. Kim, Y.K. Kwak, S.G. Hong, Flexural testing of reinforced concrete beams with recycled concrete aggregates (with Appendix), ACI Struct. J. 111 (3) (2014).
[109] D. Pedro, J. de Brito, L. Evangelista, Performance of concrete made with aggregates recycled from precasting industry waste: influence of the crushing process, Mater. Struct. (2014) 1–14.
[110] M. Pepe, R.D. Toledo Filho, E.A. Koenders, E. Martinelli, Alternative processing procedures for recycled aggregates in structural concrete, Constr. Build. Mater. 69 (2014) 124–132.
[111] C. Thomas, I. Sosa, J. Setién, J.A. Polanco, A.I. Cimentada, Evaluation of the fatigue behavior of recycled aggregate concrete, J. Clean Prod. 65 (2014) 397–405.
[112] S. Capitanio, S. Hayes, M. Mak, M. Murdock, Design of RAC filled FRP Tubers as Columns for New Construction. Final Year Honor's Research Project Report, The University of Adelaide, 2014.
[113] A.H. Gandomi, G.J. Yun, A.H. Alavi, An evolutionary approach for modeling of shear strength of RC deep beams, Mater. Struct. 46 (12) (2011) 2109–2119.
[114] A.H. Gandomi, A.H. Alavi, M. Mousavi, S.M. Tabatabaei, A hybrid computational approach to derive new ground-motion attenuation equations, Eng. Appl. Artif. Intell. 24 (4) (2011) 717–732.
[115] A. Baykasoglu, H. Gullub, H. Canakcıb, L. Ozbakırc, Prediction of compressive and tensile strength of limestone via genetic programming, Expert Syst. Appl. 35 (1–2) (2008) 111–123.
[116] J.R. Koza, Genetic Programming: On the Programming of Computers by Means of Natural Selection, MIT Press, Cambridge, MA, 1992.
[117] H. Mefteh, O. Kebaïli, H. Oucief, L. Berredjem, N. Arabi, Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete, J. Clean. Prod. 54 (2013) 282–288.
[118] AS3600-2009, Australian Standard for Concrete Structures, 2009. S.A, North Sydney.
[119] ACI 318-11, Building Code Requirements for Structural Concrete and Commentary, PCA Notes on ACI 318-11: With Design Applications, ACI International, Farmington Hills, Mich, 2011.
[120] Canadian Standard. C S A. A23.3-04, Design of Concrete Structures, Canadian Standard Association, 2004.
[121] British Standards Institution, Eurocode 2: Design of Concrete Structures: Part 1-1: General Rules and Rules for Buildings, British Standards Institution, 2004.
[122] Japan Society of Civil Engineers, Standard Specification for Concrete Structure, JSCE, Tokyo, Japan, 2007.
[123] Japanese Civil Institute, Guidelines for Control of Cracking of Mass Concrete 2008, Japan Concrete Institute, 2008.
[124] New Zealand Standard, Concrete Structures Standard. NZS 3101:2006. The Design of Concrete Structures, 2006. Wellington, New Zealand.

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