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Determination of the mechanical properties of recycled brick aggregate concrete by multivariate regression analysis

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Abstract:
This study presents regression models for prediction of compressive strength and modulus of elasticity, applying variables such as the percentage of recycled brick aggregate replacement, cement content, and water-cement ratio. A comprehensive database was constructed, comprising data from 180 experimental tests conducted on recycled brick aggregate concrete. The database includes the findings of compressive strength and modulus of elasticity testing. Multivariate statistical analysis was performed on the data and prediction models were created. During the review of the existing literature, a research gap was observed, where the modulus of elasticity was always expressed with dependence on compressive strength. The modulus of elasticity and compressive strength are modelled separately using the values of the contents of the concrete mixture. From the derived equations, the relationship that the modulus of elasticity is the second root of the compressive strength is recognized, which is in accordance with the functional relationships of the modulus of elasticity and compressive strength determined by previous authors. These models were then evaluated and confirmed using a subset of 20 samples for compressive strength and 13 samples for modulus of elasticity, which were excluded from the main database. The main results confirmed the applicability of the proposed equations with acceptable accuracy for initial concrete mixtures and thus, can be used as guidelines by future researchers.

Keywords:
recycled aggregate; multivariate regression analysis; crushed brick; compressive strength; modulus of elasticity

1 Introduction

Massive demolition of old structures has a significant impact on the environment because of the increasing amount of construction waste [1-3]. It is necessary to encourage the recycling and use of such materials in the construction of new buildings and thus to highlight the rational use and preservation of natural materials from the perspective of sustainability and ecology [4-5]. The production and use of recycled materials are economically acceptable. However, some countries still find it difficult to accept new methods of concrete production because the introduction of new methodologies requires significant financial resources. Therefore, the less-developed countries hold on to the traditional methods of concrete production [6].

The possible applications of different recycled materials have been studied over the last 20 years. Researchers have confirmed the application of recycled brick aggregate (RBA) to recycled brick aggregate concrete (RBAC) for precast concrete elements, prefabricated wall slabs, and pavers [7]. The conclusions of previous studies conducted on RBAC in comparison with natural aggregate concrete (NAC) are: the decrease of compressive strength [1, 8-9], equal compressive strength as NAC with the use of RBA with additives [10-11], decrease of tensile strength [1-2, 10, 12], stronger interfacial transition zone between recycled brick aggregate and cement paste [10, 13], lower modulus of elasticity [1, 9, 14-16], greater shrinking that can be stabilised with properly selected fraction [9–10, 17], positive effect of polymer in the RBAC [18], higher water absorption [9], lower resistance to freezing and thawing [12, 18-19], higher wear resistance [20-21], lower thermal conductivity [18, 22] and better fire resistance [10, 23-26].

Furthermore, few studies have investigated the effect of concrete mixture components on the modulus of elasticity of RBAC. Some studies [9, 27] presented formulae for estimating the modulus of elasticity of NAC, which may not be applicable for RBAC because, according to some authors [28-30], the modulus of elasticity is closely related to the properties of the aggregate and cement content; a higher cement content causes a greater decrease in the modulus of elasticity. Some equations for predicting the modulus of elasticity of RBAC have already been proposed [27, 31-34] and their applicability has been tested.

The main research gap observed in these studies, which propose a formula for the modulus of elasticity with RBA, is the consistent expression of the modulus of elasticity in relation to compressive strength. The objective of this study was to autonomously determine the modulus of elasticity without requiring knowledge of the compressive strength. It is important to be able to as accurately as possible predict the compressive strength and modulus of elasticity in advance to determine the composition of the mixture.

This study aims to assess the impact of concrete mixture components on the general material qualities of RBAC by applying multivariate regression models. The two objectives are as follows:

- The first objective of this study is to investigate the effect of different components of concrete mixtures on the compressive strength of RBAC concrete. Further, this research aims to develop an equation that can accurately predict the compressive strength of RBAC based on its components.
- The second objective of this study is to investigate the effects of different components of concrete mixtures on the modulus of elasticity of RBAC concrete. In addition, it aims to propose an equation that is not directly dependent on the compressive strength.

The proposed equations were compared with existing equations to predict the compressive strength and modulus of elasticity of the RBA concrete. This study is expected to provide valuable insights into the prediction of compressive strength and modulus of elasticity of RBAC concrete. The predictive factors considered were the quantity and proportion of the recycled brick, water-to-cement (w/c) ratio, and cement content in the concrete mixture.

2 Methods

2.1 Experimental database

For research purposes, to achieve greater variability and higher accuracy, an experimental database of 180 samples from different studies was compiled (Table 1). This table also provides information on the number of samples contributed by each author and aggregate type. The compiled database included the quantities of materials used in the preparation of concrete mixtures.

The input data parameters for the concrete mixture components included cement, water-to-cement ratio (w/c), crushed brick ratio (CB 0-4) for fine aggregates with a particle size of 0-4 mm, crushed brick ratio (CB 4-16) for coarse aggregates with a particle size of 4-16 mm, natural aggregate ratio (NA 0-4) for fine aggregates with a particle size of 0-4 mm, and natural aggregate ratio (NA 4-16) for coarse aggregate with a particle size of 4-16 mm. The total ratio of fine aggregates was consistently 100 %, and the total ratio of coarse aggregates was also 100 %. Percentages are presented in terms of mass. The concept of data normalisation has been introduced previously, resulting in reduced variability and improved predictability of the data. The output data parameters for the concrete mixture components included the compressive strength measured on the 28th day and the modulus of elasticity. The recycled aggregate used in the experiments consisted of crushed brick and tile as well as recycled brick, tile, and ceramic bushes.

Table 1. Database of experimental samples for RBAC

No. of references	Ref.	Author and year	No. of samples	Aggregate type
1	[29]	Miličević, 2014.	62	crushed brick and tile
2	[9]	Debieb & Kenai, 2008.	16	recycled brick and limestone
3	[16]	Bretschhneider & Ruhl, 1998.	5	recycled brick
4	[17]	Khatib, 2005.	5	recycled brick
5	[38]	Cachim, 2009.	10	recycled brick
6	[39]	Poon et al., 2007-1.	3	recycled brick and tile
7	[35]	Aliabdo et al., 2014.	22	crushed clay brick
8	[40]	Giridhar et al., 2015.	6	ceramic bush
9	[18]	Janković, 2001.	12	crushed brick
10	[36]	Cavalline, 2012.	4	recycled brick
11	[41]	Al-Azzawi, 2016.	5	crushed mosaic tiles
12	[37]	Martins, 2013.	4	crushed brick
13	[32]	Rashid, 2012.	5	crushed brick
14	[33]	Rashid, 2009.	3	crushed brick
15	[42]	Topcu & Canbaz, 2007.	18	crushed brick

The general distributions of the input and output parameters are listed in Table 2. The minimum value of the cement amount was 250 kg [18, 35], and the maximum value was 576 kg [33]. Furthermore, the lowest w/c ratio is 0,32 when only coarse aggregates were used for the recycled material [36], whereas the highest w/c ratio is 1.12 for the sample with 100 % of the recycled material of fine and coarse aggregates [18]. In this case, a high w/c ratio could be related to the porosity of the recycled material. Fine and coarse aggregates, for both recycled and natural aggregates, are always in the range of 0-100 %. The contribution of aggregates to the total concrete mixture was approximately 75 % by mass. From the output data, it can be noted that the lowest compressive strength at the age of 28 days was 8,7 MPa [29] for a sample with 75 % of fine recycled aggregates and the highest compressive strength was 61,75 MPa [29] in the sample with 100 % of coarse natural aggregates. Further, the lowest modulus of elasticity of 8,5 GPa [35] can be noted for samples with 100 % fine recycled aggregates and 100 % coarse recycled aggregates and with the lowest cement content of 250 kg. The highest modulus of elasticity of 39,9 GPa [37] was obtained for the sample with 100 % fine and 100 % coarse natural aggregates.

Table 2. Data range of input and output parameters

	Parameter	Minimum	Maximum	Average
Input data	Cement [kg]	250,00	576,00	364,03
	w/c ratio	0,32	1,12	0,56
	CB 0-4 [%]	0,00	100,00	35,50
	CB 4-16 [%]	0,00	100,00	49,17
	NA 0-4 [%]	0,00	100,00	64,50
	NA 4-16 [%]	0,00	100,00	50,53
Output data	fck,exp [MPa]	8,70	61,75	28,03
	Ec,exp [GPa]	8,50	39,90	22,38

Where w/c denotes water to cement ratio, CB crushed brick, NA natural aggregate, fck,exp compressive strength at the age of 28 days, Ec,exp modulus of elasticity.

2.2 Database modelling

The distribution of the data in the compiled database of 180 samples is shown in Figures 1-4 using box plots. These box plots illustrate the characteristics of a single variable with associated basic parts: the median, interquartile range (25th-75th percentile), range of non-outliers, any outliers, and extreme values. If the dataset contains outliers, which are data points that exhibit significantly higher or lower values than the rest of the data, these outliers are also marked.

Figures 1 and 2 illustrate the relationship between the compressive strength and varying proportions of recycled material CB 0-4 mm and CB 4-16 mm, respectively. Similarities can be observed in Figures 3 and 4 with respect to the modulus of elasticity.

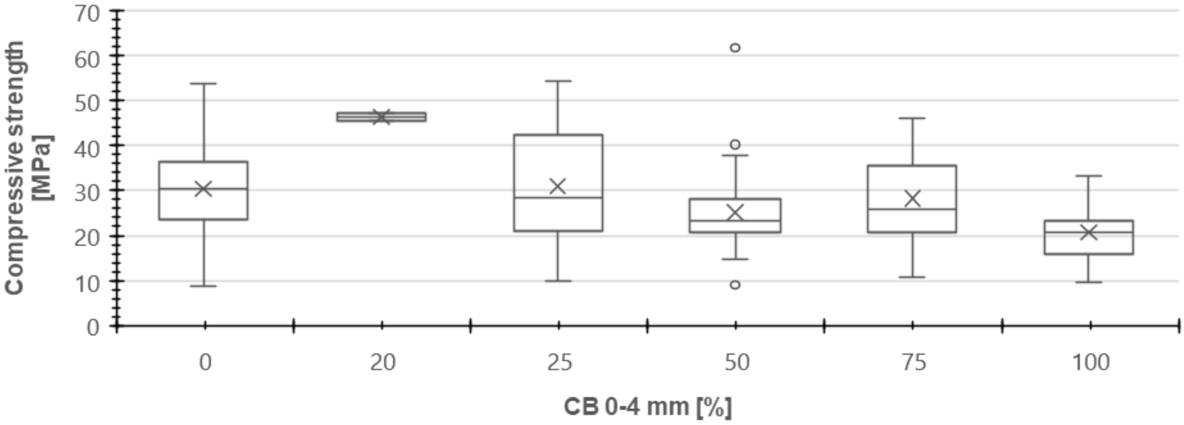

Figure 1. Box Plot of Compressive strength grouped by CB 0-4 mm

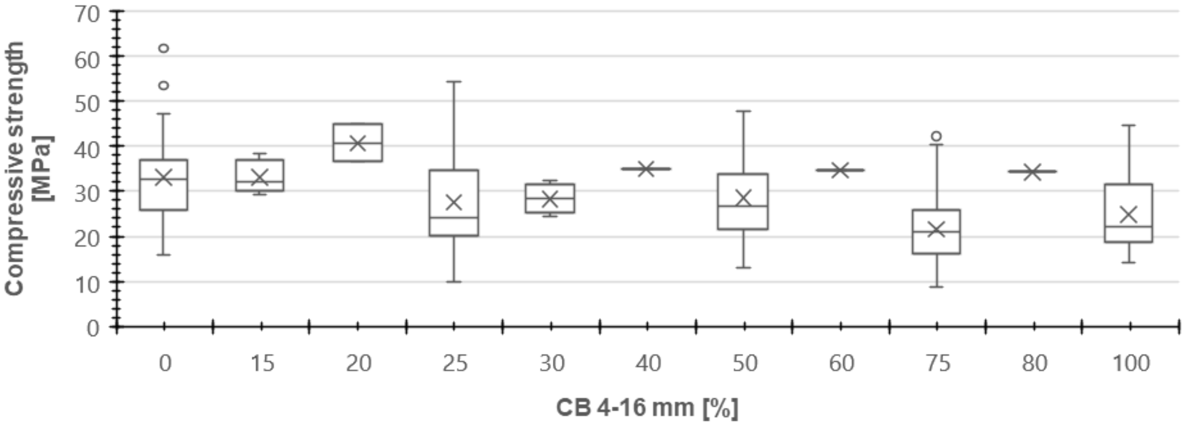

Figure 2. Box Plot of Compressive strength grouped by CB 4-16 mm

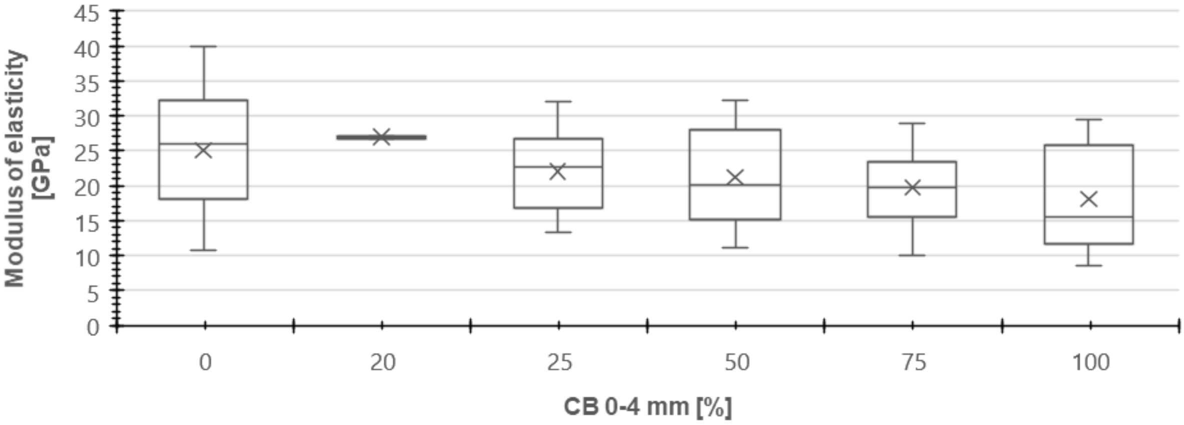

Figure 3. Box Plot of Modulus of elasticity grouped by CB 0-4 mm

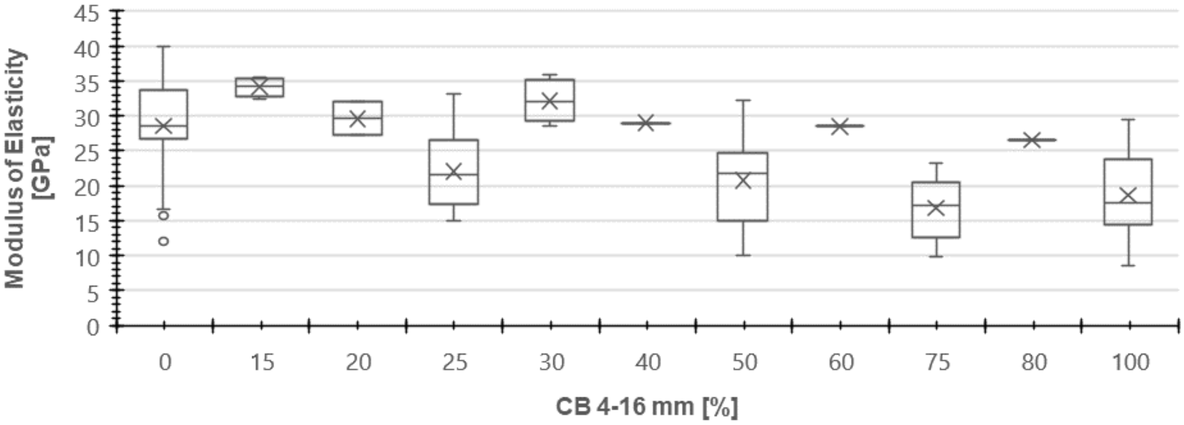

Figure 4. Box Plot of Modulus of elasticity grouped by CB 4-16 mm

2.3 Multivariate regression models

Multivariate regression analysis was used to investigate the effect of RBA on the mechanical properties of RBAC and to propose equations for estimating its compressive strength and modulus of elasticity. New relations were derived from the compiled database using statistical software tools such as "Statistica 13.5" [43] and "R" [44]. Multivariate regression analysis was used for each of the aforementioned mechanical properties using two independent variables: crushed brick of 0-4 mm and crushed brick of 4-16 mm. The following variables and their interactions were included as predictors: amount of cement, w/c ratio, CB 0-4 mm ratio, CB 4-16 mm ratio, and contribution of aggregates to the total concrete mixture.

2.4 Analysis of the experimental database

2.4.1 Prediction model for compressive strength and modulus of elasticity of RBAC

Multivariate regression models have been built to examine the potential substitution of natural fine and coarse aggregates with fine and coarse crushed brick aggregates across a range of proportions, spanning from 0-100 %. Table 3 presents the newly proposed formulae for determining the compressive strength and modulus of elasticity of RBAC. The coefficient estimates that are generated by the regression analysis for the compressive strength $f_{ck,RBAC}$ are shown in Table 4. The coefficient estimates for the modulus of elasticity, $E_{c,RBAC}$ are listed in Table 5. The tables presented in this paper show several outcomes, including standard errors and Pr values, indicating the presence of statistically significant differences. In addition, the tables include information on the t-values. The models provided in this study did not diverge from the assumption of constant error variance. This is indicated by the non-constant variance score test p-values, which are greater than 0.1 for both the compressive strength (p = 0,10682) and modulus of elasticity (p = 0,24194). There is no evidence of heteroscedasticity. Further, the Shapiro–Wilk normality test did not indicate any departure from the normality in the standardised residuals, as presented by the p-values of 0,007849 for the compressive strength and 0,08653 for the modulus of elasticity.

Table 3. Final regression models for the prediction of the mechanical properties of RBAC

Mechanical property	Final regression model
compressive strength $\sqrt{\mathrm{f_{ck,RBAC}}}$	$a_0 + a_1 \cdot CB_{0-4} + a_2 \cdot CB_{4-16} + a_3 \cdot cem + \varepsilon$
modulus of elasticity $E_{c,RBAC}$	$b_0 + b_1 \cdot CB_{0-4} + b_2 \cdot CB_{4-16} + b_3 \cdot w/c + b_4 \cdot CB_{0-4} \cdot CB_{4-16} + \epsilon$

Where a_0, a_1, a_2, a_3, a_4, b_0, b_1, b_2, b_3, b_4 denote regression coefficients; CB_{0-4} replacement level of natural fine aggregate with crushed brick aggregate 0-4 mm [%]; CB_{4-16} replacement level of natural coarse aggregate with crushed brick aggregate 4-16 mm [%]; *cem* amount of the cement in the concrete mix [kg]; w/c water to cement ratio; ε – standard error.

Table 4. Results of the regression analysis and coefficient estimation – compressive strength $f_{ck,RBAC}$

Coefficient	Estimate	Standard error	t value	Pr (>|t|)
a_0	3,79926	0,36543	10,397	< 2e-16
a_1	-0,00663	0,00168	-3,947	0,00011
a_2	-0,00738	0,00165	-4,471	1,39e-05
a_3	0,00552	0,00095	5,794	3,10e-08

Table 5. Results of the regression analysis and coefficient estimation – Modulus of Elasticity $E_{c,RBAC}$

Coefficient	Estimate	Standard error	t value	Pr (>|t|)
b_0	34,68801	1,89587	18,297	< 2e-16
b_1	-0,10797	0,02026	-5,328	3,02e-07
b_2	-0,13135	0,01502	-8,748	1,77e-15
b_3	-7,29191	3,18855	-2,287	0,02340
b_4	0,00105	0,00029	3,649	0,00035

Proposed equation for compressive strength of RBAC is given in Eq. 1:

$$f_{ck,RBAC} = (3{,}79926 - 0{,}00663 \cdot CB_{0-4} - 0{,}00738 \cdot CB_{4-16} + 0{,}00552 \cdot cem + \varepsilon)^2 \qquad (1)$$

With non-constant variance score test: Chi-square = 2,60071, Df = 1, p = 0,10682; and Shapiro–Wilk normality test: W = 0,97889, p-value = 0,007849.
Final equation for modulus of elasticity of RBAC is given in Eq. 2:

$$E_{c,RBAC} = 34{,}68801 - 0{,}10797 \cdot CB_{0-4} - 0{,}13135 \cdot CB_{4-16} - 7{,}29191 \cdot w/c + 0{,}00105 \cdot CB_{0-4} \cdot CB_{4-16} + \varepsilon \qquad (2)$$

With non-constant variance score test: Chi square = 1,369256, Df = 1, p = 0,24194; and Shapiro-Wilk normality test: W = 0,98668, p-value = 0,08653.
Figure 5 shows the experimental results in the form of dots, with three lines placed alongside them representing the model-fitted values with confidence intervals indicating the precision of the compressive strength of RBAC in relation to the quantity of cement. Values of CB 0-4 mm and CB 4-16 mm were fixed, whereas the cement values varied.
The thinnest line represents the lowest substitution of natural aggregates with crushed brick CB 0-4 mm (0 %) and CB 4-16 mm (0 %). The thickest line represents the highest quantities of these variables in the database (100 %), whereas the median line represents the estimated values in the database. Hence, it can be noted that the lines do not present straightness but rather correspond to segments of a parabolic curve. However, within this range, the degree of curvature was not prominently expressed.

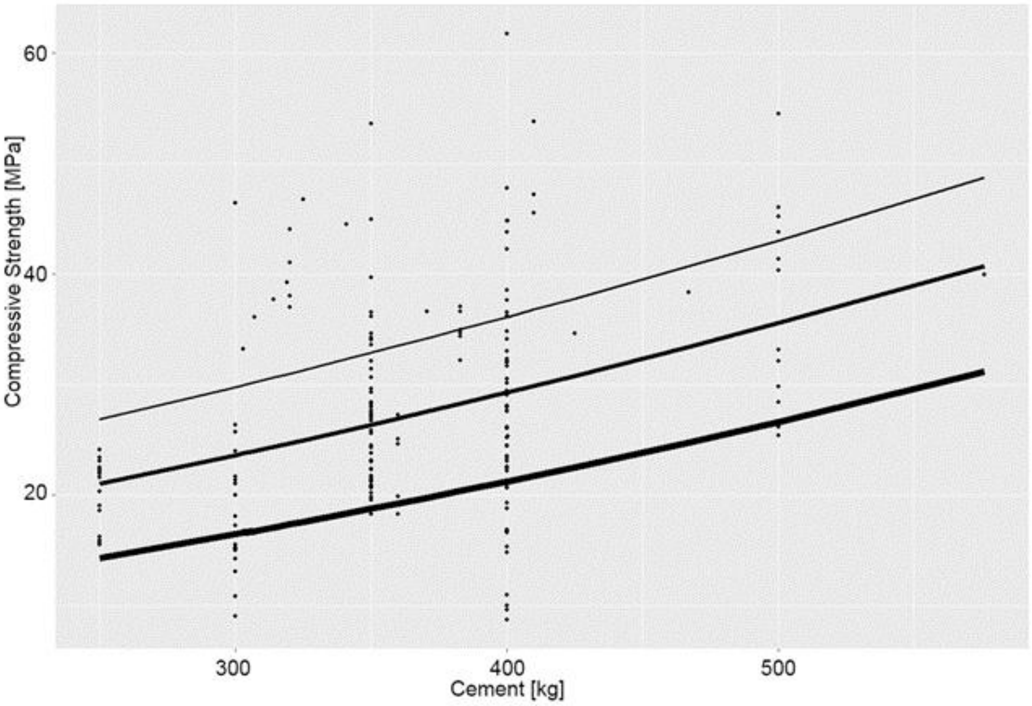

Figure 5. Model-fitted values for compressive strength of RBAC in relation with the amount of cement

The prediction of the model for the modulus of elasticity with respect to the values of various independent variables is shown in three graphs (Figures 6-8). These graphs also show the standard prediction error, which is marked by the grey region.

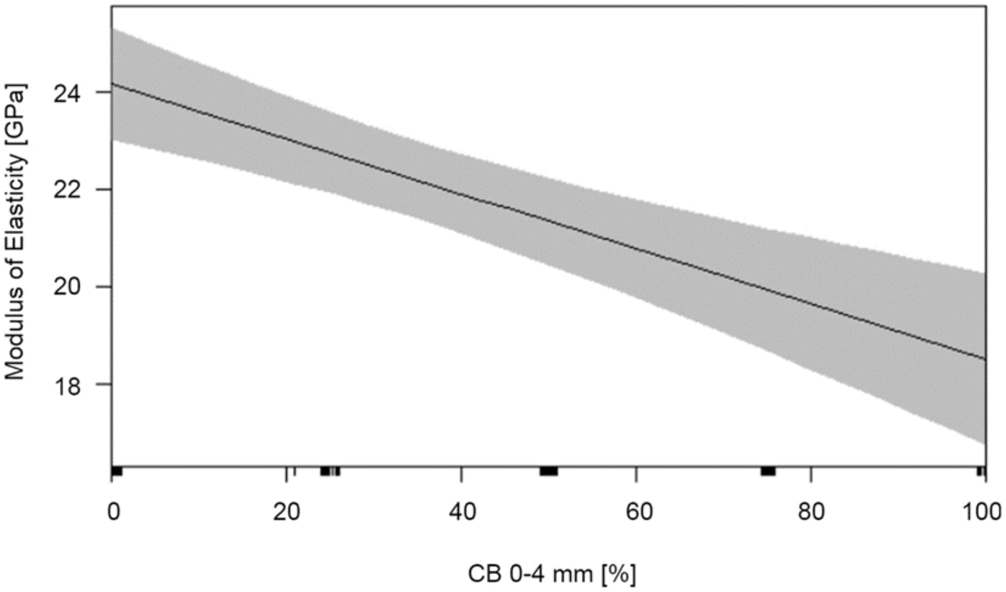

Figure 6. Model-fitted values for modulus of elasticity of RBAC in relation with the amount of CB 0-4 mm

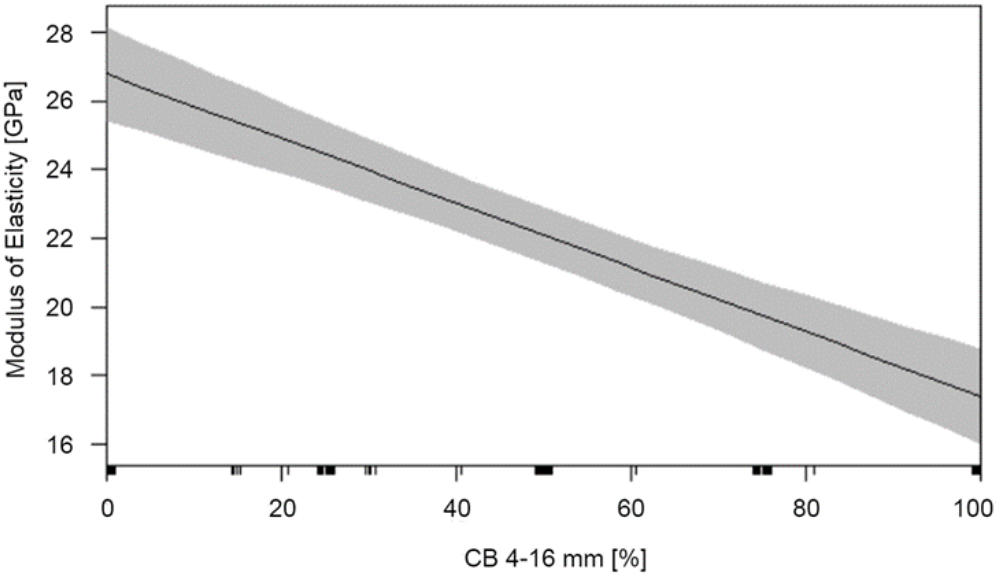

Figure 7. Model-fitted values for modulus of elasticity of RBAC in relation with the amount of CB 4-16 mm

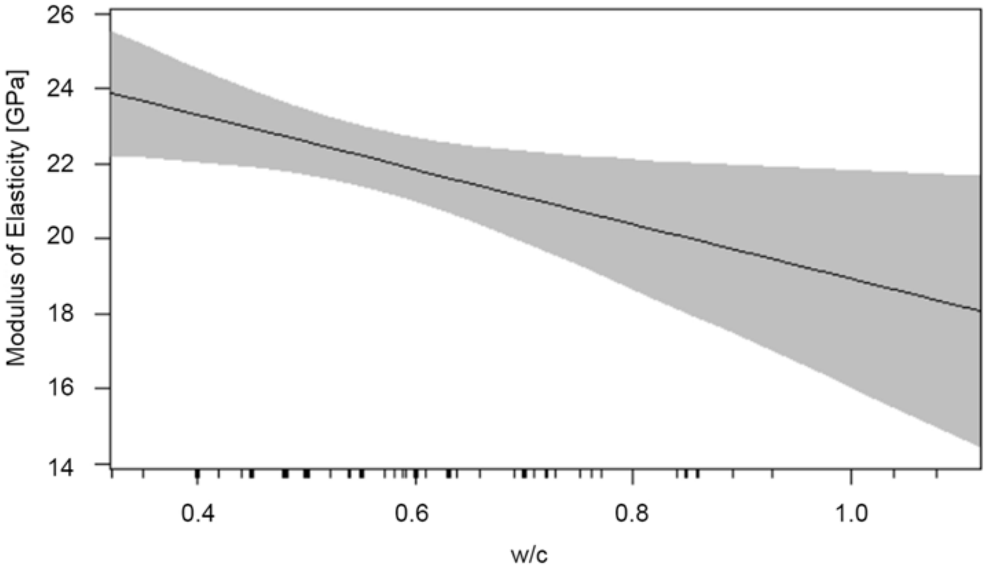

Figure 8. Model-fitted values for modulus of elasticity of RBAC in relation with water to water-to-cement ratio

The statistical significance of the interaction between CB 0-4 mm and CB 4-16 mm is evident (Figure 9). The slope of the prediction line for the modulus of elasticity, which is based on a CB of 0-4 mm, depends on the value of CB of 4-16 mm. The thickest line represents 0 % of CB 0-4 mm replacement, followed by lines indicating 20, 25, 50, 75, and 100 % of CB 0-4 mm replacement. Therefore, a model-fitted value was constructed based on the average w/c value, as it does not impact the slope of the line. By modifying the value of w/c, the entire image was vertically translated, either upward or downward. Furthermore, it is evident that the modulus of elasticity is most significantly influenced by variations in the CB 4-16 mm range, particularly when there is a complete absence of the CB 0-4 mm replacement. As the replacement value of CB 0-4 mm increased, the impact of this change decreased.

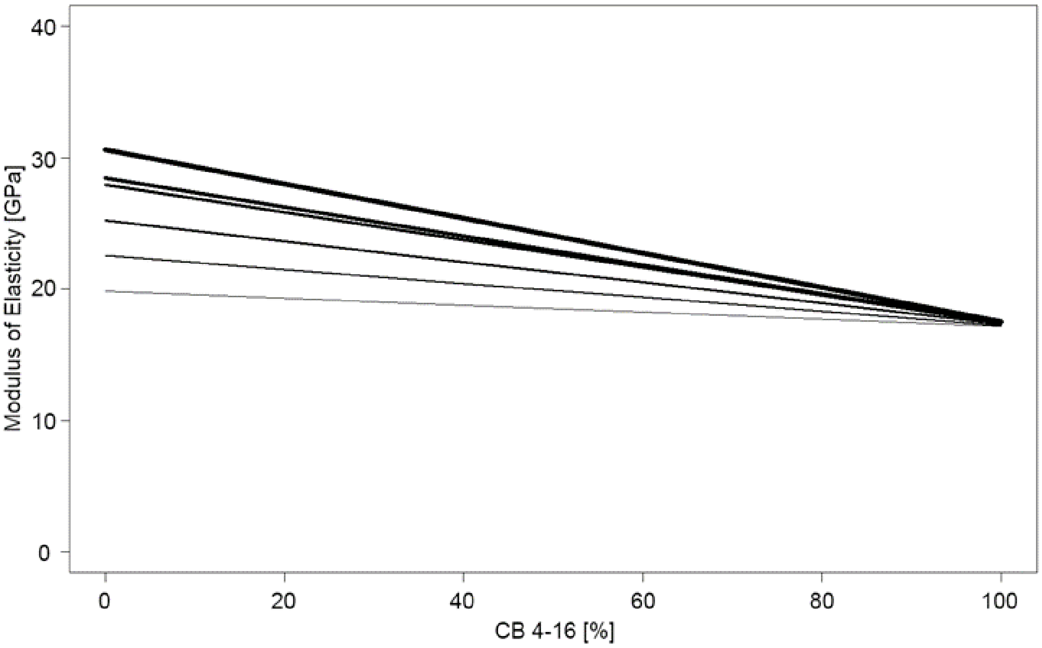

Figure 9. Model-fitted values for modulus of elasticity of RBAC in relation with the interaction of CB 0-4 mm and CB 4-16 mm

Figure 10 illustrates the model-fitted values representing the relationship between the modulus of elasticity and the interaction between CB 4-16 mm and CB 0-4 mm. The dots in the graph represent the theoretical values calculated using the obtained models. The model was created based on the predictor values from the database. The dots represent the estimated elastic modulus values. Dots with higher brightness levels indicate a greater contribution of the CB 0-4 mm.

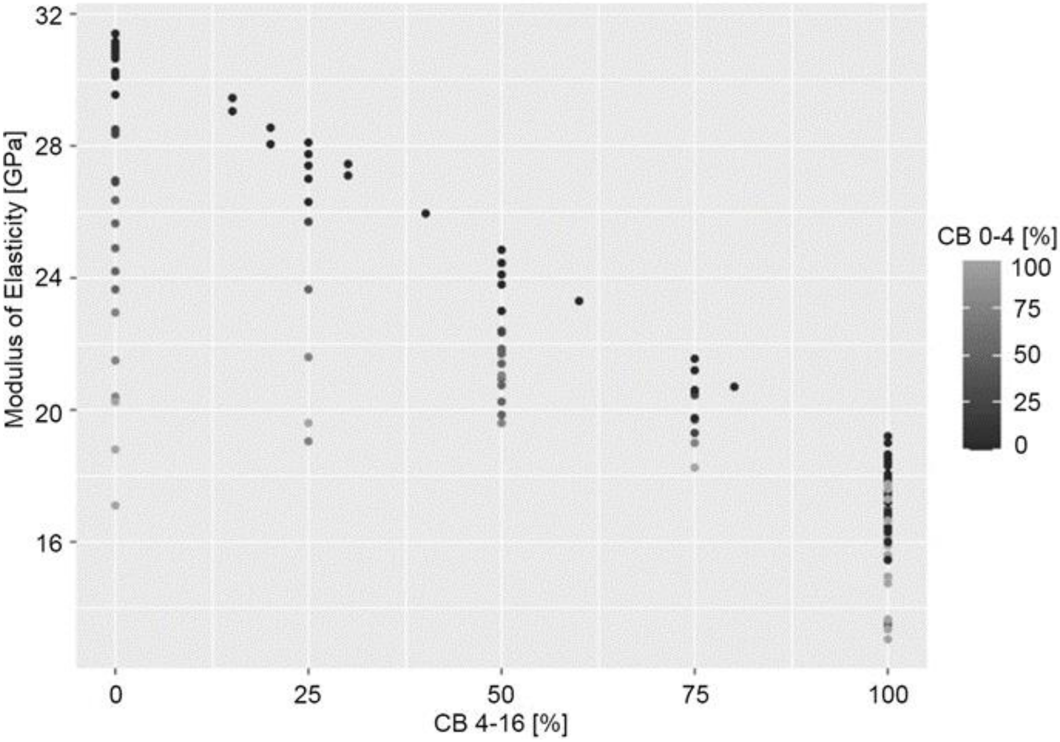

Figure 10. Model-fitted values for the modulus of elasticity of RBAC

Similarly, the model-fitted values for the modulus of elasticity in relation to the interaction between CB 0-4 mm and CB 4-16 mm are shown in Figure 11. Dots with higher brightness levels indicate a greater contribution of a CB4-16 mm.

The research is concluded by presenting the graphs in Figures 12 and 13, which provide guidance for the achievable compressive strength and modulus of elasticity using recycled fine and coarse aggregates in comparison to natural fine and coarse aggregates. The calculations for determining the compressive strength incorporated a cement quantity of 350 kg, whereas the equation for calculating the modulus of elasticity involved a water-to-cement ratio (w/c) of 0,55.

For instance, while aiming for a compressive strength of 30 MPa, it is possible to create a mixture consisting of 30 % fine recycled aggregate CB 0-4 mm (with the remaining 70 % being natural fine aggregates) and 5 % coarse recycled aggregates CB 4-16 mm (with the remaining 95 % being natural coarse aggregates). When the desired modulus of elasticity was 25 GPa, it was possible to create a mixture consisting of 40 % fine recycled aggregate CB 0-4 mm (with the remaining 60 % being natural fine aggregates) and 20 % coarse recycled aggregate CB 4-16 mm (with the remaining 80 % being natural coarse aggregates). Hence, alternative ratios of the target compressive strength and modulus of elasticity can be obtained, as shown in the graphs.

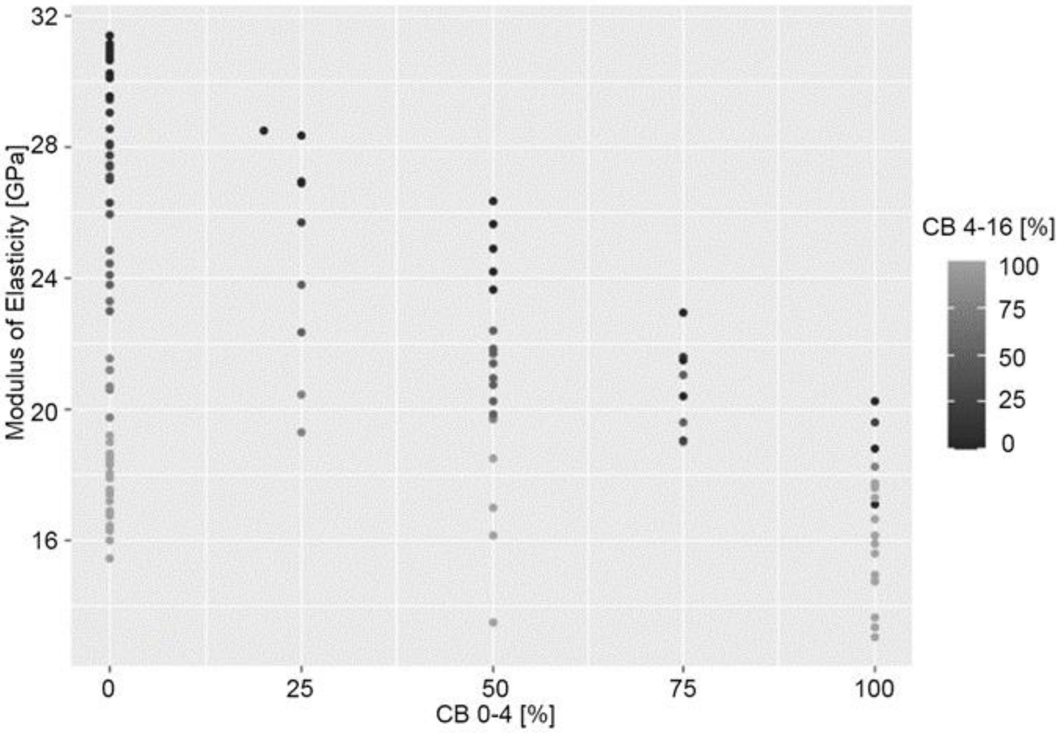

Figure 11. Model-fitted values for the modulus of elasticity of RBAC

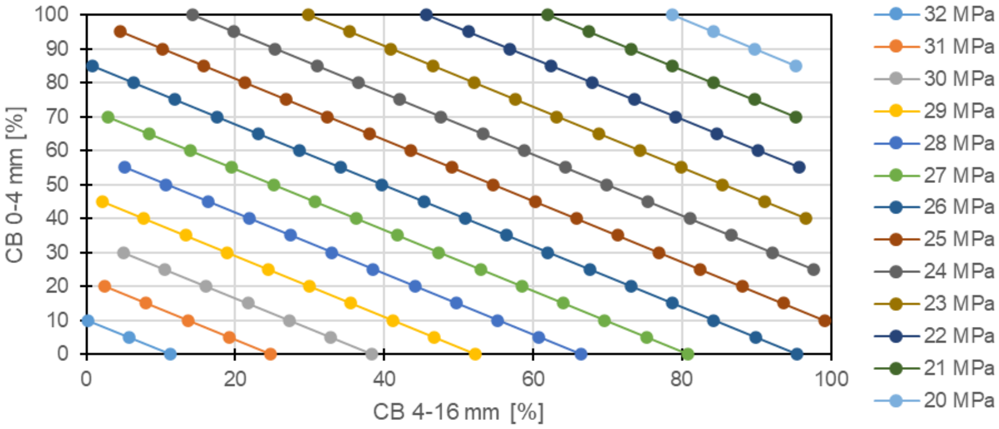

Figure 12. Predictions for the compressive strength of RBAC (Eq. 1); cement 350 kg; boundary condition (min 20 MPa, max 32 MPa)

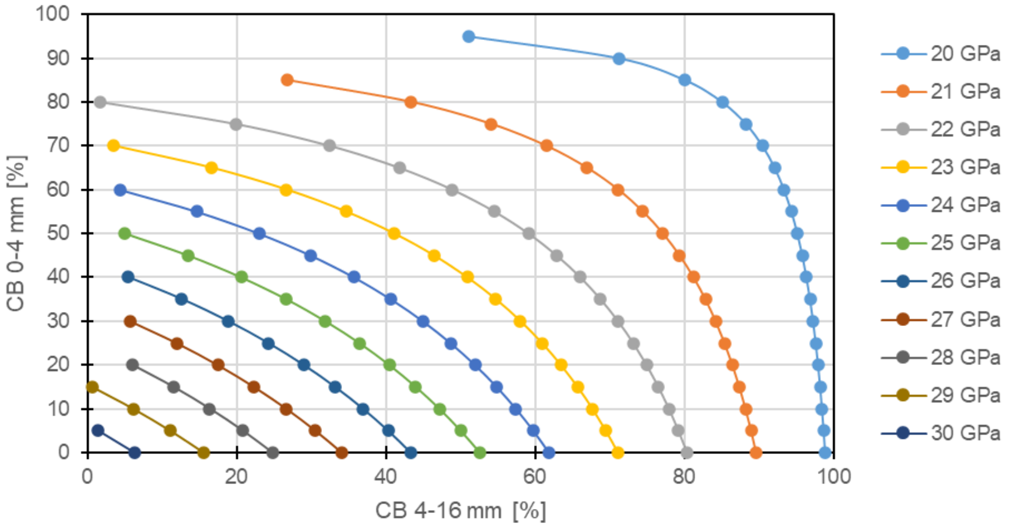

Figure 13. Predictions for modulus of elasticity of RBAC (Eq. 2); w/c = 0,55; boundary condition (min 20 GPa, max 30 GPa)

3 Evaluation of the proposed equations for compressive strength and modulus of elasticity of RBAC

To validate the prediction models for the compressive strength, the experimental results obtained from the samples were used with the provided equations. The incorporation of a new database was within the scope of the existing database, and data normalisation was implemented. The results are summarised in Table 6.

Table 6. Verification of the prediction model for compressive strength of RBAC from this study

Mixture	**Cement** (kg)	**w/c**	**CB 0-4** (%)	**CB 4-16** (%)	**$f_{ck,exp}$** (MPa)	**$f_{ck,RBAC}$ Eq. 1** (MPa)	**Absolute error** (MPa)	**Relative error** (%)
C1 [45]	400,0	0,50	0	25	39,36	33,91	5,45	13,85
C2 [45]	400,0	0,50	50	25	25,53	30,16	4,63	18,13
C3 [45]	400,0	0,50	0	75	31,95	29,75	2,20	6,89
C4 [6]	340,0	0,45	0	100	25,00	24,39	0,61	2,45
C5 [6]	340,0	0,55	0	100	22,00	24,39	2,39	10,85
C6 [6]	340,0	0,45	0	100	25,00	24,39	0,61	2,45
C7 [6]	340,0	0,45	0	100	20,00	24,39	4,39	21,93
C8 [6]	340,0	0,45	0	100	28,50	24,39	4,11	14,43
C9 [6]	340,0	0,45	0	100	22,50	24,39	1,89	8,39
C10 [6]	340,0	0,45	0	100	21,00	24,39	3,39	16,13
C11 [6]	340,0	0,45	0	100	31,00	24,39	6,61	21,33
C12 [6]	340,0	0,45	0	100	29,00	24,39	4,61	15,91
C13 [3]	390,0	0,44	0	100	21,00	27,19	6,19	29,47
C14 [46]	380,0	0,58	0	25	30,00	32,64	2,64	8,78
C15 [46]	380,0	0,58	0	50	25,00	30,56	5,56	22,24
C16 [46]	380,0	0,58	0	75	35,00	28,55	6,45	18,41
C17 [46]	380,0	0,58	0	100	29,00	26,62	2,38	8,22
C18 [47]	253,5	0,75	0	100	17,20	19,90	2,70	15,69
C19 [47]	277,5	0,69	0	100	20,60	21,10	0,50	2,42
C20 [47]	303,0	0,63	0	100	24,10	22,41	1,69	7,01
						standard deviation	**1,93**	**-**
							average	**13,25**

Both the standard deviation, which was within the range of 1,98; and the average relative error, which was within the range of 13,25 %, demonstrated strong positive correlation between the observed data and the equations that were used in the theory.

The verification of the prediction models for the modulus of elasticity is shown in Table 7, which shows a standard deviation of 3,75, and an average relative error of 12,59 %.

Therefore, both the proposed prediction models can serve as valuable resources for future researchers analysing the possible application of recycled brick aggregate in concrete. These models can aid in the formulation of preliminary concrete mixtures with a satisfactory level of precision.

To make a comparison with other proposed equations, Table 8 presents a review of the existing equations for predicting the modulus of elasticity of RBAC.

Table 7. Verification of the prediction model for the modulus of elasticity of RBAC from this study

Mixture	**Cement** (kg)	**w/c**	**CB 0-4** (%)	**CB 4-16** (%)	$E_{c,\,exp}$ (GPa)	$E_{c,RBAC}$ **Eq. 2** (GPa)	**Absolute error** (GPa)	**Relative error** (%)
C1 [46]	400	0,50	0	25	41,85	27,76	14,09	33,67
C2 [46]	400	0,50	50	25	19,26	23,67	4,41	22,89
C3 [46]	400	0,50	0	75	22,60	21,19	1,41	6,24
C4 [6]	340	0,45	0	100	24,00	18,27	5,73	23,87
C5 [6]	340	0,55	0	100	18,00	17,54	0,46	2,54
C6 [6]	340	0,45	0	100	18,00	18,27	0,27	1,51
C7 [6]	340	0,45	0	100	16,00	18,27	2,27	14,20
C8 [6]	340	0,45	0	100	20,00	18,27	1,73	8,64
C9 [6]	340	0,45	0	100	16,50	18,27	1,77	10,74
C10 [6]	340	0,45	0	100	18,00	18,27	0,27	1,51
C11 [6]	340	0,45	0	100	19,00	18,27	0,73	3,83
C12 [6]	340	0,45	0	100	17,00	18,27	1,27	7,48
C13 [3]	390	0,44	0	100	14,50	18,34	3,84	26,51
						standard deviation	**3,75**	**-**
							average	**12,90**

Table 8. Equations for predicting the modulus of elasticity of RBAC from other researchers

Authors	**Suggested expression for** $E_{c,RBAC}$	**Equation**
Mensur et al. [34]	$E_{c,RBAC} = 4050{,}00\sqrt{f_{ck,RBAC}}$ [MPa]	(3)
Rashid et al. [33]	$E_{c,RBAC} = 3113{,}81\sqrt{f_{ck,RBAC}}$ [MPa]	(4)
Akhtaruzzaman and Hasnat [27]	$E_{c,RBAC} = 3321{,}40\sqrt{f_{ck,RBAC}}$ [MPa]	(5)
Rashid et al. [32]	$E_{c,RBAC} = 5324{,}00\sqrt{f_{ck,RBAC}}-1218$ [MPa]	(6)
Miličević et al. [31]	$E_{c,RBAC} = 4735{,}70 \cdot f_{ck,RBAC}{}^{0{,}4255}$ [MPa]	(7)

In Table 9 and Figure 14, the equations proposed by other researchers are evaluated and compared. The standard deviation ranges from 4,16-5,77 in comparison with that of the proposed equation. Based on this analysis, it can be confirmed that the proposed equations have a satisfactory level of accuracy in estimating both the compressive strength and modulus of elasticity of RBAC materials.

Table 9. Evaluation of the proposed equations for $E_{c,RBAC}$ (GPa)

Mix	$f_{ck,exp}$ (MPa)	$E_{c,exp}$ (GPa)	$E_{c,RBAC}$ Eq.3 [34] (GPa)	Abs. error	$E_{c,RBAC}$ Eq. 4 [33] (GPa)	Abs. error	$E_{c,RBAC}$ Eq. 5 [27] (GPa)	Abs. error	$E_{c,RBAC}$ Eq. 6 [32] (GPa)	Abs. error	$E_{c,RBAC}$ Eq. 7 [31] (GPa)	Abs. error
C1 [46]	39,36	41,85	25,41	16,44	19,54	22,31	20,84	21,01	21,22	20,63	22,60	19,25
C2 [46]	25,53	19,26	20,46	1,20	15,73	3,53	16,78	2,48	14,72	4,54	18,80	0,46
C3 [46]	31,95	22,60	22,89	0,29	17,60	5,00	18,77	3,83	17,91	4,69	20,68	1,92
C4 [6]	25,00	24,00	20,25	3,75	15,57	8,43	16,61	7,39	14,44	9,56	18,63	5,37
C5 [6]	22,00	18,00	19,00	1,00	14,61	3,39	15,58	2,42	12,79	5,21	17,64	0,36
C6 [6]	25,00	18,00	20,25	2,25	15,57	2,43	16,61	1,39	14,44	3,56	18,63	0,63
C7 [6]	20,00	16,00	18,11	2,11	13,93	2,07	14,85	1,15	11,63	4,37	16,94	0,94
C8 [6]	28,50	20,00	21,62	1,62	16,62	3,38	17,73	2,27	16,24	3,76	19,70	0,30
C9 [6]	22,50	16,50	19,21	2,71	14,77	1,73	15,75	0,75	13,07	3,43	17,81	1,31
C10 [6]	21,00	18,00	18,56	0,56	14,27	3,73	15,22	2,78	12,22	5,78	17,30	0,70
C11 [6]	31,00	19,00	22,55	3,55	17,34	1,66	18,49	0,51	17,46	1,54	20,42	1,42
C12 [6]	29,00	17,00	21,81	4,81	16,77	0,23	17,89	0,89	16,49	0,51	19,84	2,84
C13 [3]	21,00	14,50	18,56	4,06	14,27	0,23	15,22	0,72	12,22	2,28	17,30	2,80
St. Dev.	-	-	-	**4,16**	-	**5,77**	-	**5,53**	-	**5,08**	-	**5,10**

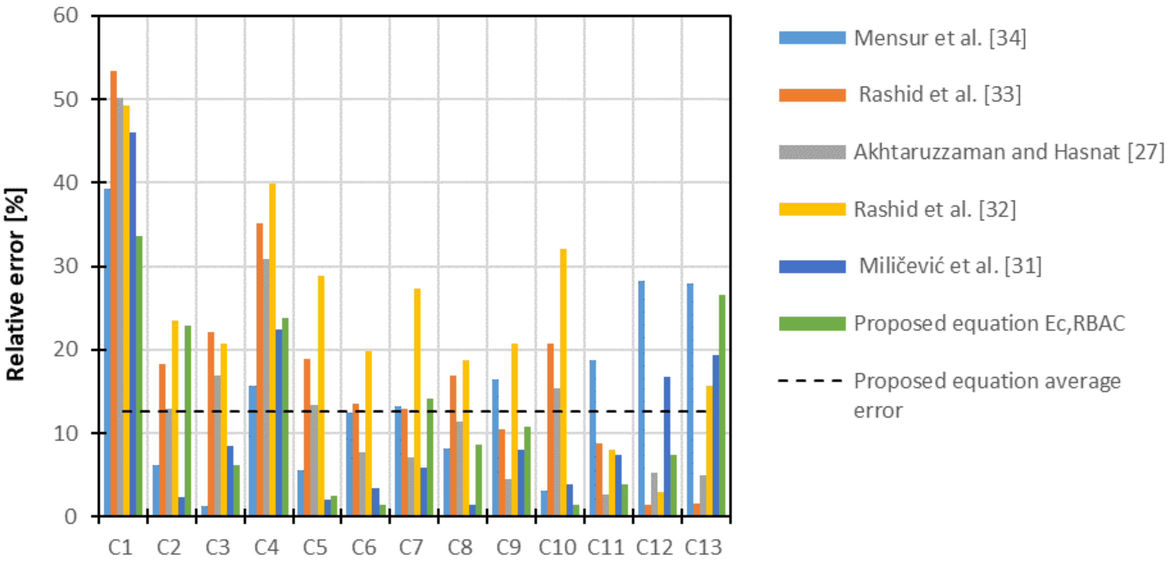

Figure 14. Relative errors of evaluation of the proposed equations based on Tables 8 and 9

4 Conclusions

The purpose of this study was to evaluate the effectiveness of multivariate regression analysis in predicting the compressive strength and modulus of elasticity of recycled brick aggregate concrete. A database including 180 experimental samples was compiled containing input data based on the proportion of crushed brick, natural aggregate, amount of cement, and water-to-cement ratio (w/c).

Novel equations were proposed to develop prediction models for estimating the compressive strength and modulus of elasticity. The prediction models were validated using the sample database, and they indicated a good correlation.

The study presents several noteworthy findings that can be summarised as follows:

- The authors have developed and validated models for accurately predicting the compressive strength and modulus of elasticity of RBAC with relative average errors up to 13 % and standard deviations up to 3,75.
- The inclusion of recycled brick aggregate (RBA) in the concrete mixtures decreased the compressive strength and modulus of elasticity. However, RBA can still be used in concrete, although in limited quantities. Guidelines for the preparation of concrete mixtures with RBA to achieve the desired mechanical qualities are presented in the form of charts.
- Crushed bricks can be used with a restricted capacity to achieve the desired compressive strength within the range of 22-32 MPa, as well as the desired modulus of elasticity within the range of 20-30 GPa.
- This study revealed a significant impact of the interaction between the CB 0-4 mm and CB 4-16 mm.
- The following variables and their interactions were included as predictors in the analysis of the modulus of elasticity and compressive strength: amount of cement, w/c, percentage of CB 0-4, percentage of CB 4-16, percentage of aggregate in the mixture. Not every predictor is statistically significant; therefore, not every predictor is an integral part of the equation.

It is recommended for future research to focus on experimental testing to assess the reliability of the models. Specifically, the incorporation of varying proportions of crushed bricks within specified fractions of the mixture was suggested. This was necessary owing to the lack of experimental data in the new database required for model validation. For instance, there are insufficient quantities of fine recycled aggregate samples (CB 0-4 mm) to validate the prediction model for the modulus of elasticity.

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