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A Practical Equation for the Elastic Modulus of Recycled Aggregate Concrete

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Abstract: For greater sustainability in construction, coarse recycled aggregate concrete (RAC) is becoming popular as a replacement for natural aggregate concrete (NAC) in structures. The elastic modulus of concrete (E) is a fundamental parameter in structure design. However, the empirical equations for E of NAC cannot apply to RAC because E of RAC is lower than NAC of equal strength, which hinders the widespread use of RAC to a certain extent. This paper provides a practical equation for E of RAC based on a comprehensive statistical analysis of 1383 mixes from 154 publications, allowing designers to easily estimate E of RAC by known parameters at the design stage, such as compressive strength, replacement rate and quality of recycled aggregate. This equation is developed by introducing a reduction factor η into the empirical equation for NAC and verified by the additional experimental results. Compared with JGJ/T443-2018 (a Chinese standard), this paper provides a more reasonable and accurate estimate by analysing much more data and taking into account other factors, such as aggregate type and the volume ratio of aggregate to paste.

Keywords: recycled aggregate concrete; elastic modulus; compressive strength; replacement rate; recycled aggregate quality; practical equation

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1. Introduction

The elastic modulus of concrete is a fundamental parameter for designing concrete structures. Thus, current building codes propose practical equations for the elastic modulus, such as Equations (1) – (3) [1–3]. The elastic modulus in these equations is a function of compressive strength, a known parameter at the design stage.

$$\text{CEB-FIP}: E_{\mathrm{NAC,pred}} = 21500(f_{\mathrm{cy}}/10)^{1/3}, \tag{1}$$

$$\text{ACI 318}: E_{\mathrm{NAC,pred}} = 4730 f_{\mathrm{cy}}^{0.5}, \tag{2}$$

$$\text{GB 50010}: E_{\mathrm{NAC,pred}} = 10^5/(2.2 + 34.7/f_{\mathrm{cu}}), \tag{3}$$

where $E_{\mathrm{NAC,pred}}$ is the estimation of elastic modulus of NAC, MPa; f_{cy} is the compressive strength measured on cylinders 150/300 mm at an age of 28 days, MPa; f_{cu} is the compressive strength measured on cubes of 150 mm size at an age of 28 days, MPa.

For greater sustainability in construction, RAC has been considered as a replacement for NAC in structures. However, due to the old mortar and crushed bricks in coarse recycled aggregate (RA), the elastic modulus of RAC is lower than NAC of equal compressive strength, meaning that the equations for the elastic modulus of NAC, such as Equations (1) – (3), cannot apply to RAC. Therefore, many equations for the elastic modulus of RAC have been developed [4–11]. However, most of them are not practical for the estimation as they use many parameters unknown at the design stage, such as the detailed mix proportion of concrete, the aggregate type, the cement type, the aggregate size, the elastic modulus of the control concrete and so on.

JGJ/T443-2018 [11] (a Chinese code for recycled concrete structures) proposes a practical equation, as shown in Equation (4), for the elastic modulus of RAC by introducing a reduction factor η that depends on the quality and replacement level of RA, as shown in Equation (5). This is justified by the fact that it takes into account the influence of the elastic modulus of the mixed aggregate that mainly depends on the porosity of the aggregate affected by the quality and replacement level of RA. However, there are two problems due to the limited data for the analysis (only about 500 mixes):

1. It shows that Class I RA has no adverse effect on the elastic modulus. However, a little old mortar may be attached to Class I RA that reduces the elastic modulus, and Ohemeng et al. [4] report that RCA made with high-quality RA may gain equal or higher compressive strength but lower elastic modulus, which means η for Class I RA should be less than 1.
2. It does not distinguish the influence of Class II and III RA on the elastic modulus. However, a significant difference in porosity between Class II and III RA may lead to a different η for them.

$$E_{\mathrm{RAC,pred}} = \eta E_{\mathrm{NAC,pred}} = \eta(10^5/(2.2 + 34.7/f_{\mathrm{cu}})), \tag{4}$$

$$\eta = \{1, \text{ for Class I RA}; 0.9 + (0.3\text{-}r)/7, \text{ for Class II and III RA}\}, \tag{5}$$

where RA is classified by GB 25177-2010 [12]; $E_{\mathrm{RAC,pred}}$ is the estimation of elastic modulus of RAC, MPa; r is the replacement rate of RA by weight.

This paper does similar works with JGJ/T443-2018 but analyses more data to enable a better evaluation of the reduction factor η. A total of 1383 mixes from 154 publications are collected and analysed statistically. The correlation between η and r for different quality of RA is quantified. From this, a practical equation for the elastic modulus of RAC in the form of Equation (4) is proposed. Finally, the equation is validated by the additional laboratory tests. Designers and engineers can use the simple equation to determine the elastic modulus of RAC by known parameters at the design stage.

2. Materials and Methods

2.1. Data Collection

First, the publications related to the elastic modulus of RCA are collected.

Second, for each publication, the key information, such as the apparent density (ρ_a) and water absorption (w_a) of RA, the replacement rate of RA, the compressive strength and the elastic modulus at 28 days and the shape and size of specimens for strength test, is identified carefully and transcribed into a spreadsheet. We cross-check it to avoid incorrect entries or repeated entries.

Notes:

- The ρ_a can be calculated from the oven-dry density (ρ_{od}) and w_a, or the saturated surface dry density (ρ_{ssd}) and w_a, or the ρ_{ssd} and ρ_{od} based on Equations (6) and (7), although some publications give the ρ_{od} or ρ_{ssd} of RA rather than the ρ_a.
- This paper uses the weight replacement rate as JGJ/T443-2018 does. Some publications use the volume replacement rate while others use the weight replacement rate. In fact, there is little difference between the volume replacement rate and weight replacement rate in most cases.
- The size effect of strength is considered in this paper. The 150 mm cube compressive strength is the standard compressive strength in this paper. The conversion factors of compressive strength are shown in Table 1 [13–16] and similar conversions can be seen in References [17,18]. For example, for C60 concrete, according to Table 1, we

can multiply the 100 mm × 200 mm cylinder compressive strength by the specific conversion factor 1.12 to obtain the 150 mm cube compressive strength. The specific conversion factor 1.12 derives from Reference [15]. In Reference [15], for C60 concrete, the 150 mm cube compressive strength is approximately 1.16 times the 150 mm × 300 mm cylinder compressive strength, which is also seen in CEB-FIP model code 2010 [1], while the 150 mm × 300 mm cylinder compressive strength is approximately 0.97 times the 100 mm × 200 mm cylinder compressive strength. Therefore, the 150 mm cube compressive strength can be considered as approximately 1.12 (≈1.16 × 0.97) times the 100 mm × 200 mm cylinder compressive strength. Different kinds of tested specimens for compressive strength and elastic modulus are adopted in different publications. The size effect on elastic modulus does not exist as the elastic modulus is the property of concrete in the elastic stage while the size effect is related to the concrete fracture [19]; however, the size effect on strength is significant. The influence factors include the cross-sectional shape, the cross-sectional diameter and the height to diameter ratio; however, the decrease in strength is not significant when the height to diameter ratio is larger than 2 [13,14].

$$\rho_a = \rho_{od}/(1 + \rho_{od}/1000 - \rho_{ssd}/1000), \tag{6}$$

$$w_a = 100(\rho_{ssd}/\rho_{od} - 1), \tag{7}$$

where ρ_a, ρ_{od} and ρ_{ssd} are the apparent density, oven-dried density and saturated surface dry density, respectively, (kg/m^3); w_a is the water absorption, %.

Table 1. Conversion factors of compressive strength [13–16].

Size/Diameter × Height	Shape	Strength Grade				
		C20–C40	C50	C60	C70	C80
150 mm	Cube			1		
100 mm	Cube			0.95		
50 mm × 100 mm	Cylinder	1.17	1.13	1.03	1.01	0.99
75 mm × 150 mm	Cylinder	1.19	1.15	1.07	1.05	1.04
100 mm × 200 mm	Cylinder	1.21	1.17	1.12	1.10	1.08
120 mm × 240 mm	Cylinder	1.23	1.19	1.14	1.12	1.10
150 mm × 300 mm	Cylinder	1.25	1.20	1.16	1.14	1.12
160 mm × 320 mm	Cylinder	1.26	1.21	1.17	1.15	1.13
100 mm × 300 mm	Prism	1.23	1.23	1.18	1.15	1.13
120 mm × 360 mm	Prism	1.26	1.26	1.22	1.19	1.16
150 mm × 300 mm	Prism	1.32	1.32	1.28	1.25	1.22

2.2. Statistic Analysis

The elastic modulus of RCA normally decreases with the increasing replacement level of RA, the degree of which depends on the quality of RA. Therefore, before the statistical analysis, the data is divided into several groups according to the quality of RA. GB 25177-2010 [12] (a Chinese code for coarse recycled aggregate) provides a performance-based classification for RA, as shown in Table 2. We use it to classify data as JGJ/T443-2018 does. It is worth noting that GB 25177-2010 only specifies Class I, II and III RA; we add Class IV RA since we find that low-quality RA beyond the requirements of Class III RA can also produce usable concrete that meets the performance requirements, which uses for reference the work of Silva et al. [20]. It is also worth noting that ”>2450” means the apparent density of Class I RA should be larger than 2450 kg/m^3 and that if the apparent density of a RA is equal to 2450 kg/m^3, the RA belongs to Class II RA rather than Class I RA.

Table 2. Physical property requirements of the performance-based classification [12].

RA Class	I	II	III	IV
Apparent density (kg/m^3)	>2450	>2350	>2250	No limit
Water absorption (%)	<3	<5	<8	

The basic form of the equation we aim to develop is shown in Equation (8). The equation changes to Equation (3) when r = 0. Moreover, the coefficient k_i represents the loss in the elastic modulus due to RA. The k_i is different for each class of RA, as shown in Equation (9). Obviously, $k_4 > k_3 > k_2 > k_1 > 0$.

It seems that the k_i can be determined by linear regression based on Equation (10). However, there are problems. Here, we take the data from Luo et al. [21] and Fonseca et al. [22] as examples. As shown in Figure 1a, the elastic modulus of 100% RAC using Class I RA decreases slightly compared with NAC, while the elastic modulus of 100% RAC using Class III RA decreases significantly, which is in line with our expectations. However, when we fit the data based on Equation (10), there is an error that $k_3 < 0 < k_1$. This is because the elastic modulus of the control concrete in the work of Luo et al. (Class I RA) is much lower than the estimation from Equation (3) [21], while that of Fonseca et al. (Class III RA) is much higher [22]. The essence is that only the compressive strength of concrete, the quality class and replacement rate of RA are considered in the equation, but the other factors affecting the elastic modulus, such as aggregate type (e.g., basalt, limestone, etc.), the volume ratio of aggregate to paste, the volume ratio of coarse aggregate to fine aggregate, aggregate size and so on, are ignored. Therefore, a correction factor α, as shown in Equation (11), is introduced to Equation (12) instead of Equation (10) to consider the other factors, and $E_{RAC}/\alpha E_{NAC,pred}$ mainly depends on the quality class and replacement rate of RA, as shown in Equation (12). At this point, the accurate k_i can be gained through linear regression based on Equation (12), as shown in Figure 1b.

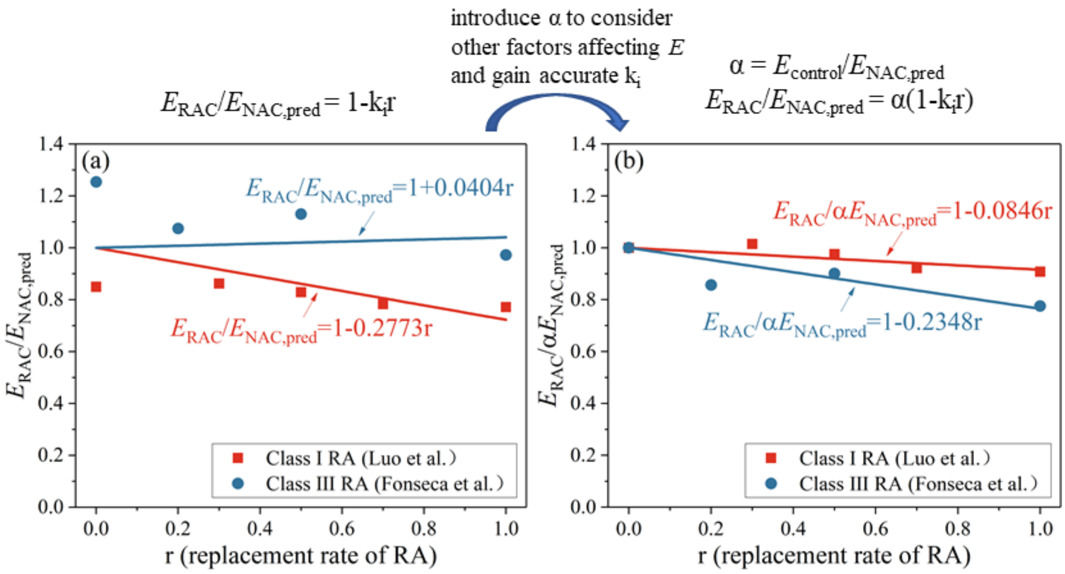

Figure 1. Introducing α to consider other factors affecting E (data source: Luo et al. [21]; Fonseca et al. [22]). (**a**) $E_{RAC}/E_{NAC,pred}$; (**b**) $E_{RAC}/\alpha E_{NAC,pred}$.

α shows the variation of E_{NAC} for a given compressive strength due to other factors, e.g., aggregate type and volume ratio of aggregate to paste. As shown in Figure 2, the value range of α is (0.65, 1.29), calculated through the statistical analysis of the 332 mixes of control concrete. It should be noted that α in eight mixes from the references [23–27] is beyond the range (μ-3σ, μ + 3σ), where μ is the mean and σ is the Standard Deviation, so α in the eight mixes are outliers. The data in these references is marked in the database and is not involved in the statistical analysis. Then, a practical equation for the elastic modulus of RCA is in the form of Equations (13) – (15).

$$E_{RAC,pred} = \eta E_{NAC,pred} = (1\text{-}k_i r)(10^5/(2.2 + 34.7/f_{cu})), \quad (8)$$

$$k_i = \{k_1, \text{ for Class I RA}; k_2, \text{ for Class II RA}; k_3, \text{ for Class III RA}; k_4, \text{ for Class IV RA}\}, \quad (9)$$

$$E_{RAC}/ (10^5/(2.2 + 34.7/f_{cu})) = (1\text{-}k_i r), \quad (10)$$

$$\alpha = E_{control}/E_{NAC,pred}, \quad (11)$$

$$E_{RAC}/ (\alpha\ (10^5/ (2.2 + 34.7/f_{cu}))) = (1\text{-}k_i r), \quad (12)$$

$$E_{RAC,pred} = 0.97(1\text{-}k_i r)(10^5/(2.2 + 34.7/f_{cu})), \quad (13)$$

$$E_{RAC,max} = 1.29(1\text{-}k_i r)(10^5/(2.2 + 34.7/f_{cu})), \quad (14)$$

$$E_{RAC,min} = 0.65(1\text{-}k_i r)(10^5/(2.2 + 34.7/f_{cu})) \quad (15)$$

where $E_{control}$ is the elastic modulus of the control concrete and the control concrete is a NAC that uses the same mix as RAC but uses natural aggregate rather than RA; E_{RAC} is the measured/actual value of elastic modulus of RAC, MPa; $E_{RAC,pred}$ is the estimation of elastic modulus of RAC, MPa; and $E_{RAC,max}/E_{RAC,min}$ are the upper/lower bound value of estimation of elastic modulus of RAC, MPa.

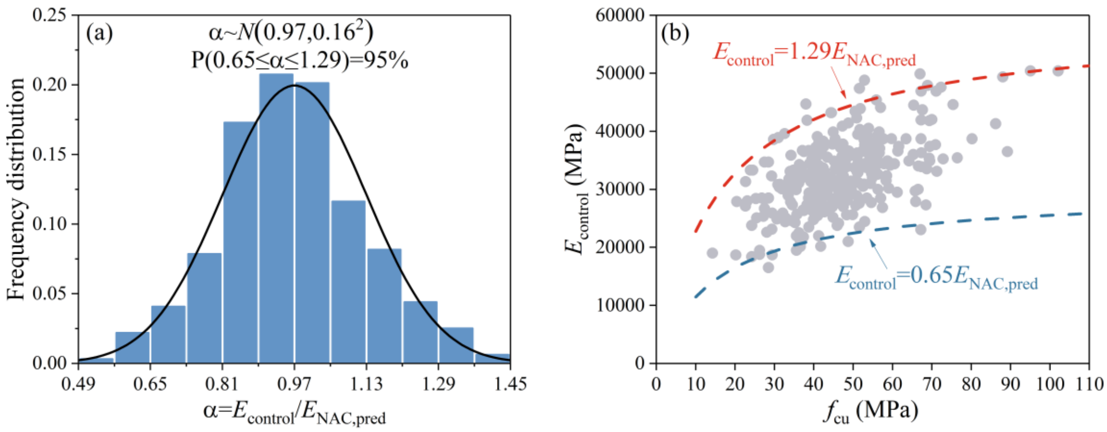

Figure 2. Distribution of α and E_{NAC} [21,22,28–174]. (**a**) $\alpha \sim N$ (0.97,0.16²); (**b**) $1.29E_{NAC,pred} \geq E_{NAC} \geq 0.65E_{NAC,pred}$.

2.3. Laboratory Tests for Verification of the Equation

The compressive strength and elastic modulus of RCA made with four classes of RA are measured, and the results are used for verification of the equation proposed in this paper.

2.3.1. Materials

The materials used are shown in Table 3. The properties of coarse aggregate are shown in Table 4. No admixture is used. RA is treated by presoaking and used under saturated surface dry (SSD) conditions.

Table 3. Materials used in the laboratory tests.

	Materials Used
Cement	PO 42.5R
Water	Tap water
Fine aggregate	Natural river sand with medium size
Natural coarse aggregate	Crushed natural stone
Class I RA	Carbonated crushed concrete
Class II RA	Crushed concrete
Class III RA	Crushed concrete
Class IV RA	Crushed concrete + crushed bricks

Table 4. Properties of coarse aggregate in the laboratory tests.

	Size (mm)	Gradation	Water Absorption (%)	Apparent Density (kg/m^3)
NA			0.7	2810
Class I RA		5–10 mm (20%)	2.5	2650
Class II RA	5–25	10–16 mm (30%)	3.6	2600
Class III RA		16–25 mm (50%)	5.5	2590
Class IV RA			8.5	2450

2.3.2. Preparation of Specimens

Three groups of control concrete are prepared with water to cement ratios of 0.6, 0.5 and 0.4, respectively. The detailed mix proportions are shown in Table 5. Sixty groups of RAC are prepared with water to cement ratios of 0.6, 0.5 and 0.4, weight replacement rates of 20%, 40%, 60%, 80%, 100% and four classes of RA, respectively. Control-0.6 means the control concrete prepared with the water to cement ratio of 0.6, while RAC-I-20-0.6 means RAC prepared with Class I RA, the weight replacement rate of 20% and a water to cement ratio of 0.6.

Table 5. Mix proportions of the control concrete in the laboratory tests (kg/m^3).

	Coarse Aggregate	Fine Aggregate	Cement	Water
Control-0.6	1088	725	367	220
Control-0.5	1096	644	440	220
Control-0.4	1122	578	500	200

2.3.3. Test for Compressive Strength and Elastic Modulus

To save raw materials, three 100 mm cubes are cast for each group for the strength test and three 100 mm × 200 mm cylinders for each group are cast for the elastic modulus test. The specimens are cured in a standard curing room for 28 days and then their compressive strength and elastic modulus are measured according to GB 50081-2019 [175]. The 100 mm cube strength is converted to the 150 mm cube strength and the 100 mm × 200 mm cylinder strength according to Table 1.

3. Dataset

A total of 1383 mixes from 154 publications are collected, as listed in Supplementary Materials [21–27,28–174]. The dataset includes 1051 RAC mixes and 332 mixes of the control concrete. However, 43 RAC mixes of data are identified as outliers and not involved in the statistical analysis, as the elastic modulus of the control concrete in these publications is too high or too low [23–27].

Most RAC mixes use the conventional replacement method, while a few mixes (26 mixes) use the equivalent mortar volume (EMV) method [86,93,101,111,115,120,126,168]. The EMV method considers the old mortar in RA as a mortar rather than a part of coarse aggregate and adjusts the coarse aggregate and fresh mortar content of the mix accordingly to achieve the same total mortar volume as the control mix. Due to the same total mortar volume, the elastic modulus of the RAC mixes designed by the EMV method is independent of quality and replacement rate of RA and not lower than NAC of equal strength, as shown in Figure 3. However, studies of the EMV method are limited [176]. Therefore, this paper still focuses on the RAC mixes designed by the conventional method.

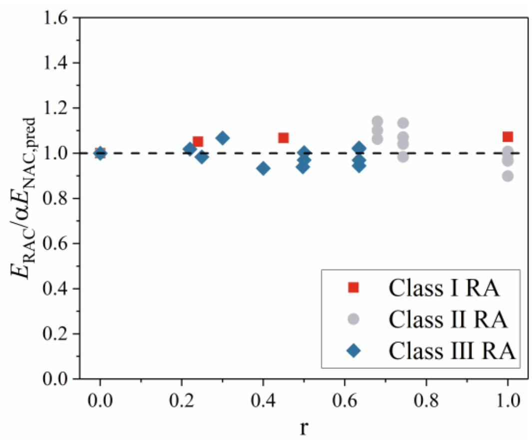

Figure 3. Comparison of elastic moduli of RAC designed by EMV method and NAC of equal strength [86,93,101,111,115,120,126,168].

Figure 4a, b present the distribution of $E_{RAC}/E_{NAC,pred}$ and the relationship between E_{RAC} and f_{cu} of 982 RAC mixes produced with different quality and replacement levels of RA, respectively. Ninety-five per cent of E_{RAC} are in the range ($0.552E_{NAC,pred}$, $1.168E_{NAC,pred}$), while 95% of E_{NAC} are in the range ($0.65E_{NAC,pred}$, $1.29E_{NAC,pred}$), as shown in Section 2.2 (Figure 2). A significant reduction in the elastic modulus due to RA can be seen. The lower bound value of $E_{RAC}/E_{NAC,pred}$ in this work is 0.552 while the value calculated by R.V. Silva et al. is 0.61 [5]. The figure of 0.552 may be more accurate as we use much more data. If the quality and replacement level of RA in RAC are unknown, Equations (16) – (18) can be used to estimate the elastic modulus of RAC. Note that the use of increasing RA content has a significant impact on the elastic modulus, and more so if these exhibit low quality. Therefore, the prediction of the elastic modulus of RAC can be improved if the quality and replacement level of RA are taken into account.

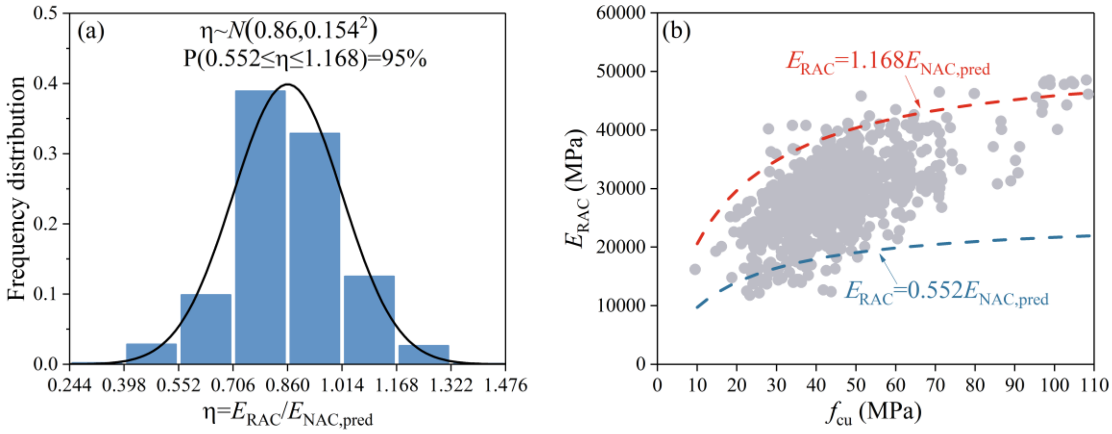

Figure 4. Distribution of η and E_{RAC} [21,22,28–167,169–174]. (**a**) η~$N(0.86,0.154^2)$; (**b**) $1.168E_{NAC,pred} \geq E_{RAC} \geq 0.552E_{NAC,pred}$.

$$E_{RAC,pred} = 0.86(10^5/(2.2 + 34.7/f_{cu})), \quad (16)$$

$$E_{RAC,max} = 1.168(10^5/(2.2 + 34.7/f_{cu})), \quad (17)$$

$$E_{RAC,min} = 0.552(10^5/(2.2 + 34.7/f_{cu})) \quad (18)$$

4. Practical Equation for the Elastic Modulus

Figure 5a–h present the relationships between $E_{RAC}/\alpha E_{NAC,pred}$, $E_{RAC}/E_{NAC,pred}$ and r of RAC mixes produced with different quality of RA, respectively. Although the R^2 obtained in this work seems low, there is a very strong correlation between $E_{RAC}/\alpha E_{NAC,pred}$ and r considering the large sample size. It should be noted that R^2 is influenced by the sample size. From a statistical point of view, the critical value of R^2 decreases with the increase of sample size and R^2 > the critical value means there is a very strong correlation, and the critical value is 0.033 (0.1829^2) when the sample size is 82 [177]. The R^2 obtained in this work is much higher than the critical value.

The results reveal that even if Class I RA is used, the elastic modulus of RAC is still lower than NAC and only slightly higher than RAC made with Class II RA, while the elastic modulus of RAC made with Class II RA is also only slightly higher than RAC made with Class III RA. However, it is acceptable that RAC made with Class I, II and III RA have a reduced value of elastic modulus up to approximately 20% at maximum compared to NAC of equal strength as the value is within the scatter band for NAC. It should be noted that the elastic modulus of RAC made with Class IV RA is significantly lower than NAC of equal strength when high RA replacement levels are used. Class IV RA shall be used with caution.

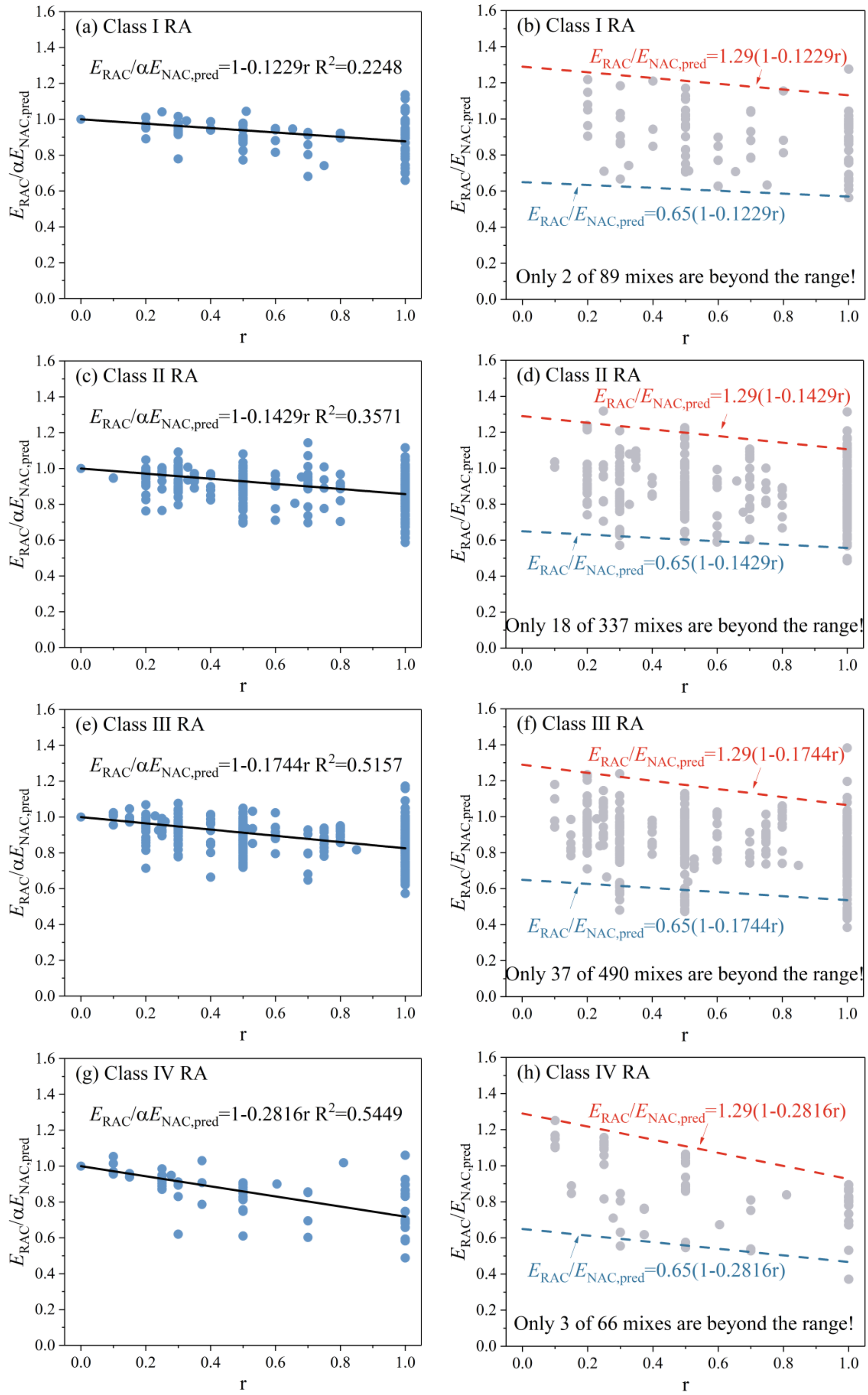
(a) Class I RA
$E_{RAC}/\alpha E_{NAC,pred}$=1-0.1229r R^2=0.2248
(b) Class I RA
$E_{RAC}/E_{NAC,pred}$=1.29(1-0.1229r)
$E_{RAC}/E_{NAC,pred}$=0.65(1-0.1229r)
Only 2 of 89 mixes are beyond the range!
(c) Class II RA
$E_{RAC}/\alpha E_{NAC,pred}$=1-0.1429r R^2=0.3571
(d) Class II RA
$E_{RAC}/E_{NAC,pred}$=1.29(1-0.1429r)
$E_{RAC}/E_{NAC,pred}$=0.65(1-0.1429r)
Only 18 of 337 mixes are beyond the range!
(e) Class III RA
$E_{RAC}/\alpha E_{NAC,pred}$=1-0.1744r R^2=0.5157
(f) Class III RA
$E_{RAC}/E_{NAC,pred}$=1.29(1-0.1744r)
$E_{RAC}/E_{NAC,pred}$=0.65(1-0.1744r)
Only 37 of 490 mixes are beyond the range!
(g) Class IV RA
$E_{RAC}/\alpha E_{NAC,pred}$=1-0.2816r R^2=0.5449
(h) Class IV RA
$E_{RAC}/E_{NAC,pred}$=1.29(1-0.2816r)
$E_{RAC}/E_{NAC,pred}$=0.65(1-0.2816r)
Only 3 of 66 mixes are beyond the range!
$E_{RAC}/\alpha E_{NAC,pred}$
$E_{RAC}/E_{NAC,pred}$
r

Figure 5. Relationships between $E_{RAC}/\alpha E_{NAC,pred}$, $E_{RAC}/E_{NAC,pred}$ and r of RAC [21,22,28–167,169–174]. (**a**) Relationship between $E_{RAC}/\alpha E_{NAC,pred}$ and r of Class I RAC; (**b**) relationship between $E_{RAC}/E_{NAC,pred}$ and r of Class I RAC; (**c**) relationship between $E_{RAC}/\alpha E_{NAC,pred}$ and r of Class II RAC; (**d**) relationship between $E_{RAC}/E_{NAC,pred}$ and r of Class II RAC; (**e**) relationship between $E_{RAC}/\alpha E_{NAC,pred}$ and r of Class III RAC; (**f**) relationship between $E_{RAC}/E_{NAC,pred}$ and r of Class III RAC; (**g**) relationship between $E_{RAC}/\alpha E_{NAC,pred}$ and r of Class IV RAC; (**h**) relationship between $E_{RAC}/E_{NAC,pred}$ and r of Class IV RAC.

α shows the variation of E due to other factors, e.g., aggregate type and volume ratio of aggregate to paste. It shows the effectiveness of the introduction of α that the obtained k_i is consistent with our expectations and most of the RAC mixes (about 94%) are in the range proposed by this work. If the quality and replacement level of RA in RAC are known, Equations (19) – (24) can be used to estimate the elastic modulus of RAC.

It should be noted that the basic equation of $E_{NAC,pred}$ uses Equation (3) proposed by the Chinese code GB 50010 [3]. Obviously, other basic equations such as Equations (1) and (2) can be also used, and the corresponding α and k_i can be easily gained by the same method as shown in Section 2.2.

$$E_{RAC,pred} = 0.97(1\text{-}0.1229r)(10^5/(2.2 + 34.7/f_{cu})), \text{ for Class I RA,} \tag{19}$$

$$E_{RAC,pred} = 0.97(1\text{-}0.1429r)(10^5/(2.2 + 34.7/f_{cu})), \text{ for Class II RA,} \tag{20}$$

$$E_{RAC,pred} = 0.97(1\text{-}0.1744r)(10^5/(2.2 + 34.7/f_{cu})), \text{ for Class III RA,} \tag{21}$$

$$E_{RAC,pred} = 0.97(1\text{-}0.2816r)(10^5/(2.2 + 34.7/f_{cu})), \text{ for Class IV RA,} \tag{22}$$

$$E_{RAC,max} = 1.33E_{RAC,pred}, \tag{23}$$

$$E_{RAC,min} = 0.67E_{RAC,pred}, \tag{24}$$

5. Verification of the Equation

The experimental results and the $E_{RAC,pred}$ estimated by Equations (19) – (22) are listed in Table 6. As shown in Table 6, $E_{RAC}/E_{RAC,pred}$ in the experiments are in the range (0.92, 1.12) which is much narrower than the range (0.67, 1.33) allowed by Equations (23) and (24). It verifies Equations (19) – (24) that the $E_{RAC,pred}$ is near E_{RAC}. In order to see this more intuitively, E_{RAC} vs. $E_{RAC,pred}$ is plotted in Figure 6.

Table 6. Experimental results and $E_{RAC,pred}$ estimated by Equations (19) – (22).

	f_c (MPa)				E (MPa)				$E_{RAC,pred}$ (MPa)	$E_{RAC}/E_{RAC,pred}$
	1	2	3	Mean	1	2	3	Mean		
Control-0.6	41.3	42.9	42.8	42.3	33600	31800	30500	31967		
Control-0.5	55.1	56.9	58	56.7	33400	35800	36100	35100		
Control-0.4	68.3	70.8	65.6	68.2	39100	38000	37100	38067		
RAC-I-20-0.6	35.8	42.2	37.9	38.6	26700	31800	29700	29400	30539	0.96
RAC-I-40-0.6	39.3	41.8	35.6	38.9	30600	29500	26800	28967	29829	0.97
RAC-I-60-0.6	37.5	35.8	38.9	37.4	29300	29200	29700	29400	28725	1.02
RAC-I-80-0.6	38.0	38.3	37.3	37.9	30400	27900	26800	28367	28066	1.01
RAC-I-100-0.6	36.5	38.9	39.5	38.3	27400	27600	29100	28033	27392	1.02
RAC-I-20-0.5	47.1	49.1	50.3	48.8	31400	32900	32700	32333	32508	0.99
RAC-I-40-0.5	53.1	54.9	47.0	51.7	31000	28800	33700	31167	32118	0.97
RAC-I-60-0.5	47.5	51.7	48.4	49.2	30400	30500	32000	30967	30925	1.00
RAC-I-80-0.5	54.5	53.4	46.9	51.6	31400	30500	31300	31067	30449	1.02
RAC-I-100-0.5	54.0	49.1	48.0	50.4	31400	30800	29600	30600	29450	1.04
RAC-I-20-0.4	52.7	59.7	62.7	58.4	35800	36300	34500	35533	33858	1.05

RAC-I-40-0.4	61.2	52.7	66.5	60.1	34600	33600	35700	34633	33212	1.04
RAC-I-60-0.4	58.6	57.7	61.2	59.2	33400	33600	35200	34067	32244	1.06
RAC-I-80-0.4	59.0	57.6	56.8	57.8	33100	33200	34500	33600	31233	1.08
RAC-I-100-0.4	59.5	68.4	65.3	64.4	32700	33200	34500	33467	31064	1.08
RAC-II-20-0.6	36.1	31.7	28.8	32.2	28200	29200	29000	28800	28749	1.00
RAC-II-40-0.6	32.1	31.0	31.0	31.4	29100	29200	28700	29000	27661	1.05
RAC-II-60-0.6	38.0	36.3	34.2	36.2	27900	27900	27400	27733	28069	0.99
RAC-II-80-0.6	35.7	34.4	32.9	34.3	28200	28900	28100	28400	26758	1.06
RAC-II-100-0.6	35.7	36.9	34.1	35.6	23700	25400	27800	25633	26180	0.98
RAC-II-20-0.5	46.9	48.8	46.2	47.3	31400	31200	31300	31300	32120	0.97
RAC-II-40-0.5	43.4	44.9	44.6	44.3	30400	31900	31000	31100	30656	1.01
RAC-II-60-0.5	44.6	45.5	43.1	44.4	30900	31200	31300	31133	29744	1.05
RAC-II-80-0.5	44.1	39.7	40.1	41.3	29700	30500	31700	30633	28258	1.08
RAC-II-100-0.5	48.0	45.6	49.8	47.8	29700	27700	30600	29333	28414	1.03
RAC-II-20-0.4	55.5	56.2	50.5	54.1	35200	33600	35700	34833	33158	1.05
RAC-II-40-0.4	54.1	53.6	56.1	54.6	35200	35100	34100	34800	32253	1.08
RAC-II-60-0.4	58.7	52.3	61.3	57.4	34200	33600	34800	34200	31625	1.08
RAC-II-80-0.4	52.3	57.2	50.1	53.2	33300	34400	33300	33667	30120	1.12
RAC-II-100-0.4	54.5	47.5	60.3	54.1	30300	31700	33700	31900	29260	1.09
RAC-III-20-0.6	33.2	35.2	35.8	34.7	27500	29200	29000	28567	29264	0.98
RAC-III-40-0.6	32.4	34.4	36.0	34.3	27200	27300	27700	27400	28087	0.98
RAC-III-60-0.6	31.7	34.1	32.9	32.9	24000	24800	25500	24767	26684	0.93
RAC-III-80-0.6	28.4	35.2	32.4	32.0	22300	24000	24800	23700	25413	0.93
RAC-III-100-0.6	36.3	29.8	29.4	31.8	21100	25400	23500	23333	24341	0.96
RAC-III-20-0.5	49.6	45.9	47.0	47.5	31000	30800	32400	31400	31945	0.98
RAC-III-40-0.5	42.6	47.3	47.5	45.8	30000	29800	29900	29900	30509	0.98
RAC-III-60-0.5	45.6	42.6	46.9	45.0	26300	28000	27200	27167	29237	0.93
RAC-III-80-0.5	44.9	45.9	44.9	45.2	26700	27100	25600	26467	28130	0.94
RAC-III-100-0.5	46.5	43.4	39.1	43	23500	24000	26000	24500	26632	0.92
RAC-III-20-0.4	54.1	55.3	60.9	56.8	34200	34400	34800	34467	33300	1.04
RAC-III-40-0.4	58.0	58.0	52.7	56.2	32600	33600	33700	33300	32031	1.04
RAC-III-60-0.4	51.4	53.5	49.7	51.5	30000	30600	30700	30433	30226	1.01
RAC-III-80-0.4	54.2	53.2	46.5	51.3	29300	28900	29000	29067	29018	1.00
RAC-III-100-0.4	46.5	52.5	45.6	48.2	28000	27200	26500	27233	27427	0.99
RAC-IV-20-0.6	33.3	36.3	31.4	33.7	25800	28300	27600	27233	28334	0.96
RAC-IV-40-0.6	32.7	32.8	32.7	32.7	26100	27300	28000	27133	26402	1.03
RAC-IV-60-0.6	30.3	28.1	29.8	29.4	22500	24800	24600	23967	23847	1.00
RAC-IV-80-0.6	33.7	31.7	34.1	33.2	23600	23400	23400	23467	23149	1.01
RAC-IV-100-0.6	30.2	26.8	34.1	30.4	18700	21400	21600	20567	20847	0.99
RAC-IV-20-0.5	44.9	45.6	47.3	45.9	28500	28900	29300	28900	30972	0.93
RAC-IV-40-0.5	45.5	46.2	42.6	44.8	28200	29900	29600	29233	28931	1.01
RAC-IV-60-0.5	45.2	40.8	45.1	43.7	25100	26100	26200	25800	26924	0.96
RAC-IV-80-0.5	47.1	43.8	39.3	43.4	25700	26500	25600	25933	25053	1.04
RAC-IV-100-0.5	37.5	40.3	37.9	38.6	23300	21000	25100	23133	22481	1.03
RAC-IV-20-0.4	61.3	59.1	55.1	58.5	31400	32300	32200	31967	32772	0.98
RAC-IV-40-0.4	51.7	51.7	54.3	52.6	31000	31600	31900	31500	30095	1.05
RAC-IV-60-0.4	55.3	48.8	46.6	50.2	28000	28500	28800	28433	27886	1.02
RAC-IV-80-0.4	46.9	55.9	51.9	51.6	25600	27800	28800	27400	26157	1.05
RAC-IV-100-0.4	47.5	46.6	45.7	46.6	22500	26000	25100	24533	23665	1.04

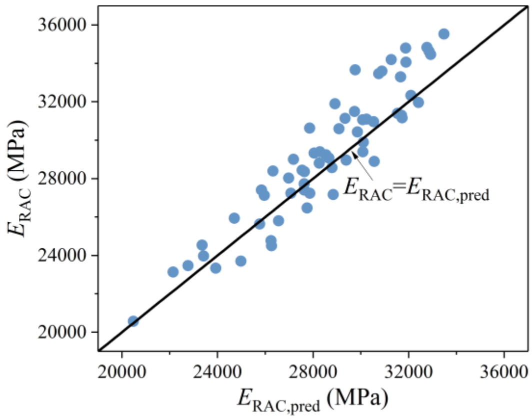

Figure 6. Comparison of $E_{RAC,pred}$ and E_{RAC} obtained in the Laboratory tests.

6. Comparison with JGJ/T443-2018

Table 7 shows values of the reduction factor η in JGJ/T443-2018 and this work for different quality of RA when r = 1, respectively. The η values in this work is more in line with our expectations as the η value for Class I RA is less than 1 and the η value for Class II RA is larger than that Class III RA, as shown in Table 7. Compared with this work, JGJ/T443 overestimates the elastic modulus of RAC using Class I RA and underestimates that of RAC using Class II RA. However, the estimation for the elastic modulus of RAC using Class III RA by JGJ/T443-2018 and this work is close.

Table 7. Values of η in JGJ/T443-2018 and this work when r = 1.

	Class I RA	Class II RA	Class III RA
JGJ/T443-2018 [11]	1	0.8	0.8
This work	0.85	0.83	0.8

7. Conclusions

Although RAC may exhibit similar compressive strength to NAC, as the RA content increases the elastic modulus decreases, the degree of which depends on the quality of RA. This paper aims to use the reduction factor η to quantify the loss of the elastic modulus and propose a practical equation for the elastic modulus of RAC based on a comprehensive statistical analysis of 1383 concrete mixes from 154 publications. Based on the results of this investigation, the following conclusions can be drawn:

- For a given compressive strength, the elastic modulus of RAC in most studies is in the range (0.552$E_{NAC,pred}$, 1.168$E_{NAC,pred}$). It should be noted that this prediction interval is applicable only when the compressive strength is known while the other factors are unknown.
- The correlation between the reduction factor η and the replacement rate for different quality of RA is determined. The results show that the reduced elastic modulus of RAC made with Class I, II or III RA is acceptable; however, the reduced elastic modulus of RAC made with high replacement rates of Class IV RA is so low that Class IV RA must be used with caution.
- The prediction interval (scatter band) of the elastic modulus of RAC is provided considering the variation of the elastic modulus due to other factors, e.g., aggregate type and volume ratio of aggregate to paste.
- JGJ/T443-2018 overestimates the elastic modulus of RAC made with Class I RA and underestimates that of RAC made with Class II RA.
- The experimental results verify the equation proposed in this work. If the replacement rate and quality (classified by the apparent density and water absorption) of

RA are known, designers and engineers can use the simple equation to determine the elastic modulus of RAC by means of the compressive strength.

It should be noted that these conclusions only apply to RAC designed by the conventional method. The elastic modulus of RAC designed by the EMV method is not lower than NAC of equal strength due to the same mortar volume. However, the related studies are limited. Therefore, further studies need to be conducted to ensure the effectiveness of the EMV method and the reliability of the results.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/article/10.3390/buildings12020187/s1.

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