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Study of basic mechanical properties of recycled concrete with various recycled coarse aggregate mixes

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Research Paper

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Three kinds of recycled aggregate concretes (RACs), with six different replacement rates at four ages, are subjected to the standard cube axial compression test to study mechanical properties. Failure modes, compressive strength, stress-strain curves, peak strain, and elastic modulus of RACs are systematically analysed. In addition, three equations are proposed for RACs to describe the relationship between the compressive strength and replacement rate. Comparison between various equations of elastic modulus and test results is presented, and then three most suitable equations are established for three kinds of RACs, including necessary modifications, especially for RAC with mixed recycled aggregates.

Key words:
waste brick, mixed recycled aggregates, compressive strength, elastic modulus, mechanical properties

Prethodno priopćenje

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Analiza osnovnih mehaničkih svojstava mješavina recikliranog betona s recikliranim krupnozrnatnim agregatom

Tri vrste recikliranog betona sa šest različitih udjela recikliranog agregata (RAC) ispitano je u četiri različite starosti kako bi se odredila njihova tlačna čvrstoća na uzorcima oblika kocke, odnosno kako bi se utvrdila njihova mehanička svojstva. Sustavno su analizirani oblici sloma, tlačna čvrstoća, krivulje naprezanja – deformacije, maksimalne deformacije te modul elastičnosti betona s recikliranim agregatom. Na temelju dobivenih rezultata predložena su tri izraza za RAC kako bi se opisao odnos između tlačne čvrstoće i udjela zamjene agregata. Razni izrazi za određivanje modula elastičnosti uspoređuju se s rezultatima ispitivanja, nakon čega se prikazuju tri najpovoljnija izraza za tri vrste RAC-a, uključujući i potrebne izmjene, naročito za RAC s miješanim recikliranim agregatom.

Ključne riječi:
otpadna opeka, miješani reciklirani agregat, tlačna čvrstoća, modul elastičnosti, mehanička svojstva

1. Introduction

In the process of construction, the use of traditional building materials creates several serious problems such as an excessive consumption of resources, pollution, and overuse of land. It is estimated that approximately 200 million tons of waste concrete are currently produced annually in the mainland of China [1]. Over recent years, the recycling potential of construction and demolition waste (CDW) has become an issue of topical interest and the main focus of waste management policies encouraging minimization. It has been recognized that development of the recycled aggregate concrete (RAC) is an efficient way of recycling waste concrete, and that it greatly contributes to sustainable development in construction industry [2, 3].

To make RAC a widely accepted structural material, a comprehensive experimental research has been conducted in recent years. With regard to RAC strength, the experimental results of Bairagi et al. [4] and Olorunsogo [5] show that the compressive strength of RAC decreases with an increase in recycled aggregate (RA). Based on a comprehensive analysis of test results from a number of scholars Wesche and Schulz [6] have established that the compressive strength of RAC is by 10 % lower than that of the ordinary concrete. However, Ridzuan et al. [7] show in their research that the strength of RAC may be improved by 2 % to 20 %. Compared to natural aggregate concrete, RAC even has many variations of compressive strength. Pereira et al. [8] point to an increasing strength variation of recycled fine aggregate concrete with 20 %-30 % or 100 % of replaced aggregate. Xiao et al. [9] have established that the compressive strength of RAC is higher than that of ordinary concrete when the replacement rate (*rr*) of recycled coarse aggregate is 50 %. Experimental results obtained by Chang [10] point to an abnormally high strength of RAC when the *rr* of recycled coarse aggregate is 50 % and 70 %. The results of Sun et al. [11] show that the compressive strength of RAC with the *rr* of 70 % and 100 % is higher than that of RAC with the *rr* of 40 %. There is no unified understanding on the compressive strength and further tests and theory are needed to determine the law of strength change. About the elastic modulus, Xiao [12] and Hu et al. [13] have found up to 45 % lower modulus of elasticity for RAC with 100 % RCA in comparison with that of ordinary concrete. Zhou et al. [14] report that the elastic modulus of RAC is by 15-26 % lower than that of ordinary concrete, depending on the qualities of the parent concrete and RCA properties. Kou et al. [15] also conclude that the elastic modulus of RAC decreases as the RCA replacement percentage increases, and that the elastic modulus of RAC with 100 % RCA (Recycled Concrete Aggregate) was about 40 % lower than that of ordinary concrete. The paper of Qasrawi and Marie [16] introduces a simple formula for the prediction of the modulus of elasticity of RCA concrete. Scholars like Etxeberria et al. [17] and Evangelista and Brito [18] conducted a series of experimental research of different RA with different replacement rate, and the results have shown that the *rr*, maximum diameter, compressive strength and moisture content of aggregate, as well as water/cement (*w/c*) ratio, can all influence mechanical performance of RAC. With an increase in the *rr* and *w/c*, the strength of RAC decreases slightly, while an increase in moisture content can improve the strength. RAC with larger particle size and better gradation has higher strength. Chen et al. [19] found that the complete stress-strain curve of RAC is similar to the curve of ordinary concrete: rising segments basically coincide while, in descending segments, RAC curve is steeper. Taking into consideration mechanical properties and economic indicators, these authors propose that 30 % to 40 % is an optimum *rr* of RAC. Test results by Poon et al. [20] show that at 28 days, the strengths of concrete prepared with different types of aggregates (air-dried, oven-dried, and saturated surface-dried) were similar. Experimental results obtained by Du [21] show that the peak stress, peak strain of the peak point and original point, increase with an increase in strength grade of RAC.

Based on the current state-of-the-art, scholars have made a large number of studies on the performance of RAC, mostly using recycled concrete aggregate (RCA) as aggregate, while a few have also used recycled brick aggregate (RBA) to replace natural aggregate (NA). More systematic research is extremely scarce. BS 8500-2 [22] also defines RA as aggregate resulting from the processing of inorganic material previously used in construction, for example crushed concrete, masonry, or brick. For a long time, bricks have been extensively used in China as a load-bearing and exterior-protection construction material. With an acceleration of urban construction and reconstruction, a lot of waste brick material will become available due to demolition of old buildings. According to incomplete statistics [23], broken brick and masonry blocks account for 30 % to 50 % of the total CDW, which reflects the rapid increase in the use of brick in China, especially as waste brick is rich in resources.

Several studies have been made on the effectiveness of using crushed clay-brick as a coarse aggregate in making concrete. Miličević has made a lot of hard work to show possible applicability of concrete that is made using partial replacement of natural aggregate with crushed bricks and roof tiles [24-26]. More comprehensively, the mixture with the highest percentage of replacement of natural aggregate by crushed brick and roof tile aggregate has the best physical, mechanical, and thermal properties for application of such concrete in precast concrete elements exposed to high temperatures, as shown in the study prepared by Miličević et al. [25] in 2016. When compared to experimental results for density, compressive and flexural strength, and modulus of elasticity, both models presented by Miličević and Kalman Šipoš [26] were found to be capable of generalizing between input and output variables with reliable predictions. Test results of Milovanović et al. point to the possibility of manufacturing concrete with RCA and RBA, which can find wide use in the building construction process

[27]. Variation in the volume of voids, water absorption, and storativity between parent concrete and RAC reduces with an increase in the strength of concrete [28]. Regarding results of the tests performed on hardened concrete, the values obtained suggest that the use of mixed RAs is feasible, but at the expense of minor losses of mechanical characteristics [29, 30]. However, their investigations used only two different RAs replacing NA, respectively, and without the use of two kinds of RAs in the same concrete.

To the best knowledge of the authors, no systematic research effort has been devoted to the investigation of mechanical properties of RAC using mixed RAs, which is why a more innovative research will be conducted in this paper. Results from a large number of researches show that: the types of RA, the replacement ratio, and the variety in age, are the most important factors for the properties of RAC. A more detailed study is necessary because of great difference of the current research results of RAC with RBA or RCA, and as few studies have been made about RAC with mixed RAs. For the *rr*, former researchers usually took 30 % or above as the differential in research range, and so the results were relatively inaccurate, and test data more precise in differential are needed for the convenience in application. As to other aspects, various properties, RAC strength in particular, are influenced by varieties in the length of curing period. Taking into account three aspects: recycled coarse aggregate type, replacement ratio and curing age, this paper uses RCA and RBA, respectively, as RA, while also using a certain proportion of the two to completely replace NA as mixed RAs. The properties of two kinds of RAs working together can thus be studied.

2. Materials and experiment

2.1. Materials

Portland cement Hailuo 42.5R, with the apparent density of ρ_c = 3100 kg/m^3, was used in this investigation. Natural river sand with the fineness modulus MX of 2.75, maximum grain size of 0.4 mm, and an apparent density of 2650 kg/m^3, was used as fine aggregate. Regular ρ_w = 1000 kg/m^3 tap water was used for the concrete mixture. Coarse aggregates include NA, RCA and RBA, and the latter two (Figure 1) were obtained from the concrete parts and masonry walls of an abandoned building situated near Hohai University, Nanjing. These elements were crushed and not pre-wetted for mix process. The results of random core drilling tests show that the strength was roughly 38-42 MPa for waste concrete, and about 12 MPa for waste brick. The same sieves were used in the selection of NA, RCA and RBA so as to obtain three kinds of coarse aggregate of the same continuous gradation. The three samples were used to test individual properties of coarse aggregates (grading, bulk density, apparent density, water absorption at 24 h, and crushing index) according to Chinese standard JGJ 52 [31]. The corresponding average results are presented in Table 1.

Figure 1. Recycled aggregates: a) RCA; b) RBA

The bulk density and apparent density of RAs are lower and water absorption and porosity values are higher compared to those of NA as a lot of old cement mortar was attached to the surface and more micro cracks were contained inside of RAs, which is in accordance with former test results [32]. Besides, the properties of RBA itself differ from NA much more compared to RCA due to its clay characteristics.

2.2. Specimen design

Specimens were designed to investigate the effects of the following parameters: (1) Coarse aggregate type, including RAC with RBA (RACI), RAC with RCA (RACII) and RAC with mixed RAs including RBA and RCA (RACIII); (2) The *rr*, i.e. 0 %, 20 %, 40 %, 60 %, 80 % and 100 %; (3) Curing age, i.e. 7, 14, 21 and 28 days. These proportions of concrete mixes were designed using the absolute volume method by assuming that the aggregates were in an air-dried condition. Meanwhile, three duplicate specimens were prepared for each RAC type. The concrete mixes were designed to cube block (150 mm × 150 mm × 150 mm) according to the ordinary concrete of strength grade C40 [33], with *w/c* ratio of 0.44 and the fine aggregate to total aggregate ratio of 0.307, as shown in Table 2.

Table 1. Properties of various coarse aggregates

Aggregate type	**Continuous grading** [mm]	**Bulk density** [kg/m^3]	**Apparent density** [kg/m^3]	**Water absorption** [%]	**Crushing index** [%]
NA	10~30	1450	2800	0.3	1.5
RCA	10~30	1389	2452	3.1	7.0
RBA	10~30	1280	1967	14.6	45.0

Table 2. Mix proportion design for RAC specimens (concrete with recycled aggregate)

Specimen group	Coarse aggregates and rate	Water [kg/m³]	Cement [kg/m³]	Sand [kg/m³]	NA [kg/m³]	RBA [kg/m³]	RCA [kg/m³]
RACI-0	RBA(0 %). NA(100 %)	185.00	420.45	574.01	1295.73	0.00	0.00
RACI-20	RBA(20 %). NA(80 %)	185.00	420.45	550.22	1056.63	185.57	0.00
RACI-40	RBA(40 %). NA(60 %)	185.00	420.45	525.64	808.10	378.46	0.00
RACI-60	RBA(60 %). NA(40 %)	185.00	420.45	500.00	549.57	579.11	0.00
RACI-80	RBA(80 %). NA(20 %)	185.00	420.45	473.31	280.43	788.00	0.00
RACI-100	RBA(100 %). NA(0 %)	185.00	420.45	445.50	0.00	1005.64	0.00
RACII-0	RCA(0 %). NA(100 %)	185.00	420.45	574.01	1295.73	0.00	0.00
RACII-20	RCA(20 %). NA(80 %)	185.00	420.45	564.21	1044.87	0.00	228.75
RACII-40	RCA(40 %). NA(60 %)	185.00	420.45	554.26	789.96	0.00	461.19
RACII-60	RCA(60 %). NA(40 %)	185.00	420.45	544.14	530.92	0.00	697.40
RACII-80	RCA(80 %). NA(20 %)	185.00	420.45	533.86	267.63	0.00	937.47
RACII-100	RCA(100 %). NA(0 %)	185.00	420.45	523.41	0.00	0.00	1181.51
RACIII-0	RBA(0 %). RCA(100 %)	185.00	420.45	523.41	0.00	0.00	1181.51
RACIII-20	RBA(20 %). RCA(80 %)	185.00	420.45	508.55	0.00	191.77	956.21
RACIII-40	RBA(40 %). RCA(60 %)	185.00	420.45	493.35	0.00	388.05	725.60
RACIII-60	RBA(60 %). RCA(40 %)	185.00	420.45	477.78	0.00	589.01	489.49
RACIII-80	RBA(80 %). RCA(20 %)	185.00	420.45	461.83	0.00	794.81	247.70
RACIII-100	RBA(100 %). RCA(0 %)	185.00	420.45	445.50	0.00	1005.64	0.00

RAC - recycled aggregate concrete, NA - natural aggregate, RCA - recycled concrete aggregate, RBA - recycled brick aggregate

2.3. Specimen casting and curing

All concrete mixes were mechanically mixed in a 50 L compulsory mixer with the following feeding order.
Firstly, appropriate proportions of cement, dry sand and water were poured into the mixer to get cement mortar, and the stirring was stopped after 1.5 minutes.
Secondly, mixed coarse aggregates were added and stirred for 2 minutes, and then the mix was immediately packed in test templets which were pre-oiled at inner walls; the specimens were removed from templets after 24 h and cured under standard conditions.

2.4. Experimental mode

The loading equipment in this investigation was a 5000 kN hydraulic testing machine, Figure 2.
The experiment was conducted in accordance to the Chinese standard GB/T 50081 [34]. Load control method with a load differential of 100 kN and load speed of about 3 kN/s was used until the specimen lost bearing capacity.

Figure 2. Loading equipment

3. Results and discussions

3.1. Failure processes and failure modes of RACs

Axial compression failure processes for three RACs were compared at 28 days. In the early loading stage, the strain

Figure 3. Failure modes: a) RACI; b) RACII; c) RACIII

was nearly linear with stress on the surface in elastic state. The stress gradually increased with the load, producing compressive deformation in the vertical direction and expansion deformation in the lateral direction. The upper and lower ends of the specimen were restrained, so as to form the hoop effect. Initial cracks emerged along the vertical direction in the middle and developed towards both ends of the specimen due to the lateral deformation, while the RACI was the first to have slight cracks, followed by RACII and RACIII. When close to the peak stress, cracks on RACI developed rapidly until sudden failure, and then the stress of the concrete quickly decreased. For other two kinds of RACs, one or several almost paralleled longitudinal cracks appeared in the middle part with a sound of cracks increasing, and the cracks gradually extended towards the upper and lower ends and finally reached corners. So the test pieces went into plastic state with the growth of strain, until the peak stress was reached or exceeded; then cracks developed rapidly, and the load passing lines inside the test pieces continued to decrease, and so the final stress plunged sharply to a compressive failure.

The remaining concrete blocks were obtained after removing debris around the surface with a dry towel. Typical failure modes of these three kinds of RACs are shown in Figure 3. The remaining concrete blocks exhibited an hourglass shape, i.e. outer concrete broke off while central concrete remained intact which is similar to that of ordinary concrete. The type and replacement rate of recycled coarse aggregate had no obvious impact on overall failure modes of the blocks. The bond surface between RBA and cement was broken and some RBAs were even pressed into powder while NA basically retained its integrity (Figure 3.a). It was established that the strength of cement matrix was much higher than the RBA in RACI. So RBA was first crushed to form the inside cavity under compression, and the net section area of concrete block was reduced due to stress concentration. Besides, the block was free of bulging due to lack of restraint in the lateral surface. Those two reasons lead to the ultimate compressive failure of RACI. The strength of the mortar between aggregate and cement was low, which led to interfacial failure between the aggregate and cement matrix, while RCA or NA still retained a block shape though some were cut off (Figure 3.b). Cracks continued to extend under compression, and the bond between the aggregate and cement failed first before the crush of aggregate due to small difference in strength between coarse aggregate and cement. The surface of RACIII block has both characteristics, which means that compression failure of RBA and detachment between the mortar and RAs could be observed at the same time (Figure 3.c).

3.2. Compressive strength of RAC

3.2.1. Influence of age

Compressive strengths (f_{cu}) of RACI, RACII and RACIII cubes at the age of 7, 14, 21 and 28 days are presented in Table 3. The f_{cu} of RAC gradually increased with the age for each *rr* and for each RAC family, which is similar to ordinary concrete.

The f_{cu} exceeds 40 MPa at the age of 28 days when the *rr* is below 20 % for RACI and RACII families, which means these RACs can be used as having the same strength grade as ordinary concrete. At 28 days of curing, all RACs reveal compressive strength losses of up to 23.48 % and 14.72 % for the RACI and RACII families, respectively. RACI and RACIII follow a similar process of change in compressive strength due to the same influential factors of the RBA content and curing age. In addition, the RCA and NA are closer in material

Table 3. Compressive strength of RACs [MPa]

RACs	RACI				RACII				RACIII			
Age	7 d	14 d	21 d	28 d	7 d	14 d	21 d	28 d	7 d	14 d	21 d	28 d
rr = 0 %	11.42	21.29	33.35	42.12	11.42	21.29	33.35	42.12	11.05	18.94	30.01	40.43
rr = 20 %	10.91	20.02	32.45	41.29	12.09	22.61	36.1	44.77	10.48	17.13	28.46	38.35
rr = 40 %	9.99	19.22	31.04	39.76	10.69	20.38	32.69	38.56	9.78	15.59	27.73	36.22
rr = 60 %	8.06	17.62	29.06	37.21	9.75	18.83	25.22	37.83	7.58	14.23	26.36	34.62
rr = 80 %	7.14	15.33	26.40	35.54	8.89	16.83	22.45	35.92	6.51	13.67	25.10	33.44
rr = 100 %	6.26	12.94	23.40	32.23	11.05	18.94	30.01	40.43	6.26	12.94	23.40	32.23
rr - share of aggregate replacement, RACI = RAC + RBA, RACII = RAC + RCA, RACIII = RAC + RBA + RCA												

properties than RBA, and so failure reasons are basically the same:
- The strength of RBA is much lower than that of NA, and so it crushed first
- The bond between RBA and cement mortar is poor, because the brick surface has low adsorption of cement paste reducing the workability of fresh concrete, which can also be clearly observed in the mixing process
- Besides, fragile residual mortar on brick surface causes stress concentration under compression, accelerating destruction of RAC
- The failure is also caused by separation of aggregates and cement mortar due to the weak bonding area between the old mortar attached to RBA and the new one, which leads to the shear failure of this area.

The f_{cu} of RACI-20, RACI-40, RACI-60, RACI-80 and RACI-100 decreases by 4.47 %, 12.52 %, 29.42 %, 37.48 % and 45.18 %, respectively, compared to RACI-0 at the age of 7 days, which confirms that there is an obvious strength decline at an early age of RAC with RBA. Because RBA has a similar strength with the early hardened cement paste as a kind of lightweight aggregate, the strength at an early age is determined by the cement paste. Hence, the application of RAC with RBA is limited at an early age and some monitoring and maintenance should be made when adopting this kind of RAC. Also, the compressive strength in RACI and RACIII families exhibits rapid growth at later age, caused by high porosity and strong water absorption of RBA, whose absorbed water is released during cement hydration, and so the RAC can maintain certain internal temperature, which helps the curing and increase in strength. For RACII, there is no stress concentration in aggregate itself due to higher strength of RCA. The main reason for the decreased strength of RACII is that the old cement mortar attached on RCA has low strength and will weaken the bond between the new cement paste and aggregates; also, internal cracks in the pressed RAC can expand easier during this axial compression, resulting in the decrement of strength.

3.2.2. Influence of replacement rate

Relative compressive strength is defined as the ratio of the compressive strength of RAC to that of the ordinary concrete without RA, as shown in Figure 4. It can be seen that f_{cu} of RACI and RACIII first decreases gradually and then rapidly with the RBA according to Figure 4. The f_{cu} decreases just from 1.97 % to 23.48 % compared to ordinary concrete for RACI when *rr* increases from 20 % to 80 %. Similarly, f_{cu} decreases from 4.01 % to 23.48 % for RACIII. Several reasons could be suggested for the reduction of compressive strength of RAC, including an increased concrete porosity and a weak aggregate-matrix interface bond. However, if the RBA content is less than 40 %, the influence on compressive strength is not significant. Then there is a significant drop once the *rr* is more than 60 % due to the low strength of RBA, when it becomes the main coarse aggregate.

Compared to ordinary concrete, the value f_{cu} of RACII-20, RACII-40, RACII-60, RACII-80 and RACII-100 at 28 days, decreases by -6.29 %, 8.45 %, 10.19 %, 14.72 % and 4.01 %, respectively. RACII-20 has the highest f_{cu} even exceeding that of ordinary concrete. This result for the low incorporation of RCA is in agreement with previous studies [8, 35]. Such good performance can be explained by:
- higher un-hydrated cement content in the mix [36] providing additional hydraulicity [37]
- the fact that the interfacial transition zone between the RCA and the cement paste may have benefited from the porosity of RCA having decreased locally, with the *w/c* ratio allowing a more effective filling by hydrated products [38]
- filler effect linked to the smaller size of RCA compared to NA [39], but only for small replacement rate (around 20 %).

A combination of these four phenomena can overcome consequences of the lower strength of RCA, thus justifying these results. With higher replacement rate the effect of lower mechanical characteristics of RCA overrides the combined effect of these phenomena. However, f_{cu} of RACII-100 (40.43 MPa) is higher than that of RAC with the *rr* beyond 40 %, while RACII-80 has the lowest f_{cu}. This phenomenon can also be observed in the studies by Pereira et al. [8] and Sun [11]. It can be explained that the bond between aggregate and cement mortar makes a small difference due to the use of only one kind of coarse aggregate, and stress concentration is not obvious. Therefore, f_{cu} is higher than that of RAC for several kinds of aggregates.

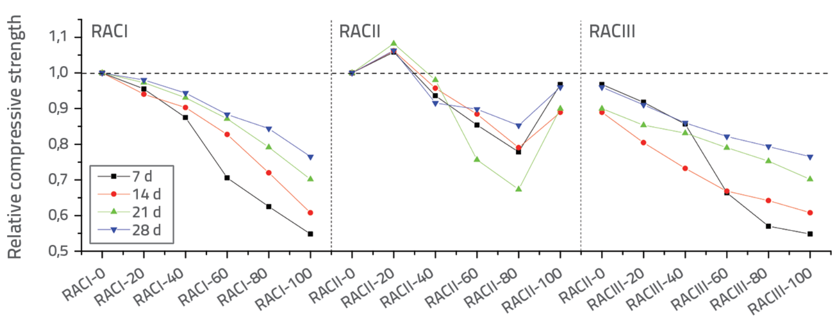


Figure 4. Relative compressive strength of RACs

3.2.3. Relationship between compressive strength and replacement rate

It is widely recognised that there is a close relationship between concrete compressive strength and the *w/c* ratio. Bolomey equation provides a good correlation between these two parameters:

$$f_{cu} = A \times f_{ce} \times (c/w - B) \tag{1}$$

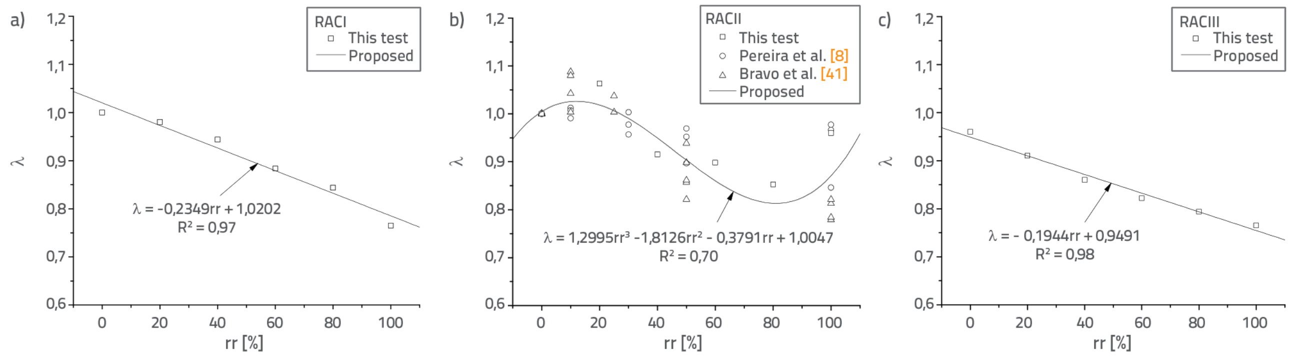


Figure 5. Proposed relation between relative compressive strength and the rr: a) RACI; b) RACII; c) RACIII

where f_{ce} is the compressive strength of cement. A and B are empirical constants, which amount to 0.46 and 0.07 for 42.5R cement according to JGJ 55 [33], or to 0.448 and 0.094 according to Zhang [40]. In this investigation, A and B are taken as 0.45 and 0.0704 according to test results for ordinary concrete.

Because of the uncertainty of RAC performance, academia has not formed a unified understanding about the relationship between the compressive strength and replacement rate, which is why conventional equations are still being explored. Bearing these principles in mind, an empirical Eq. (2) is devised to determine the cubic compressive strength (f_{cu}) as a function of the w/c ratio and rr, given that these factors indirectly define higher or lower compressive strength. Coefficient λ is considered as the influencing factor of rr through the nonlinear regression model proposed, and is valid for concrete mixes in this study.

$$f_{cu} = 0.45 \times f_{ce} \times (c/w - 0.0704) \times \lambda \tag{2}$$

These parameters were determined based on appropriate results. Coefficient λ for RACI at 28 days is proposed in Eq. (3), and it corresponds to R^2 = 0.97. Some experimental results [8, 41] with the same variation (increasing variation on compressive strength with 10 % to 30 % or 100 % replaced aggregate) are cited to increase reliability of the proposed equation, and so the coefficient λ for RACII at 28 days is proposed in Eq. (4), and it corresponds to R^2 = 0.70. The coefficient λ for RACIII at 28 d is proposed in Eq. (5), and it corresponds to R^2 = 0.98. Graphic representation of the equation proposed, coupled with the actual test results, is shown in Figure 5.

$$\lambda = -0.2349 \times rr + 1.0202 \tag{3}$$

$$\lambda = 1.2995 \times rr^3 - 1.8126 \times rr^2 + 0.3791 \times rr + 1.0047 \tag{4}$$

$$\lambda = -0.1944 \times rr + 0.9491 \tag{5}$$

3.3. Stress-strain curves

Stress-strain curves of three kinds of RACs at 28 days are shown in Figure 6. It should be noted that namely the RACIII differs greatly from former studies which mainly focused on RAC with one kind of RA. Only the ascending branch is plotted since this curve is used for the analysis of peak strain and elastic modulus. Figure 6 shows that RAC curves are greatly influenced by rr of RA. Nevertheless, the shape of the stress-strain curve for all RACs is similar to that of the ordinary concrete, which leads to the conclusion that there would be in principle no objection in the structural design process to the application of the theory of elasticity of these three kinds of RACs. The RACs are thought to be in the elastic state with linear curves, then they transfer to the elastic-plastic state with a decreased slope of curves. It is worth mentioning that RAC suffers a higher increment of strain than ordinary concrete with the same increment of stress, and this phenomenon is

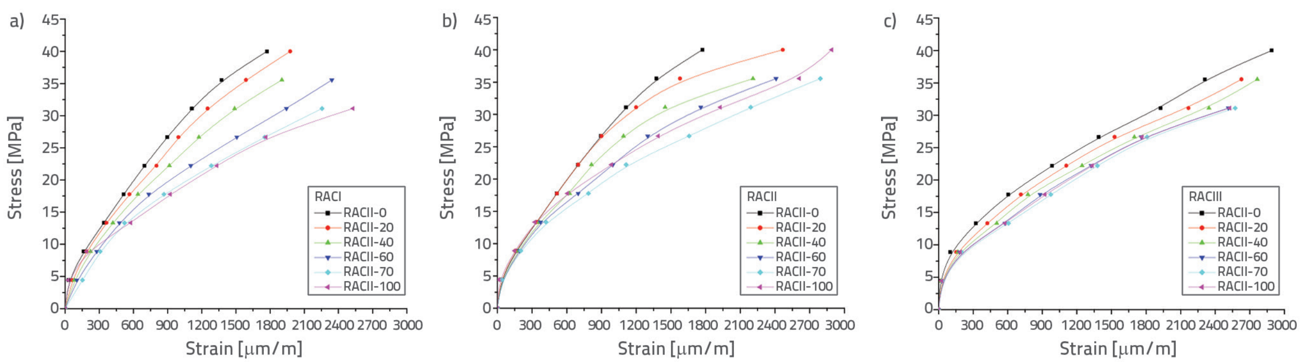


Figure 6. Stress-strain curves of RACs: a) RACI; b) RACII; c) RACIII

intensified with the *rr* of RA due to the lower elastic modulus of RA. Moreover, the presence of mortar adhering to RA, which is more compliant than NA, allows the increase of strains in the ascending branch.

3.4. Peak strain

The strain corresponding to peak stress, as shown in Figure 7, is considered to be peak strain for RAC. The ordinary concrete has the lowest peak strain of only 1773 μm/m, which is close to the generally accepted value of 2000 μm/m [42]. The RAC with all RCA has the maximum peak strain which is by about 60 % higher compared to ordinary concrete. The main reason for the increase of peak strain of RAC is the reduced elastic modulus of RAC, which leads to greater deformation. Besides, the old cement adhering to aggregate surface actually increases the gel content, which also gradually leads to increment of peak strain. RACI and RACII curves show that, if RBA or RCA is used alone as RA, the peak strain increases along with the *rr*. However, RCA has a stronger increasing effect on peak strain than RBA, as confirmed by the following two facts: The peak strain of RACIII shows a decrement with an increase in RBA content and the reduction in RCA content, and RACII-100 has higher peak strain than RACI-100.

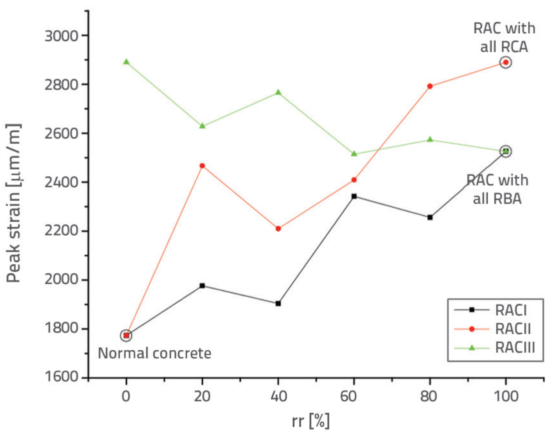


Figure 7. Peak strain of RACs

3.5. Elastic modulus

The elastic modulus of concrete reflects the linear elastic stress-strain relation which is very important in both the static and dynamic analysis of reinforced concrete structures. Because the stress-strain curve of concrete has both linear and nonlinear deformation states, various definitions of elastic modulus have been proposed worldwide. In this investigation, the elastic modulus (*E*) of RAC was determined from the stress-strain curves

$$E = (\sigma_2 - \sigma_1) / (\varepsilon_2 - 0.005\ \%) \tag{6}$$

where σ_2 is the stress corresponding to 40 % of peak load, σ_1 is the stress corresponding to a strain of 0.005 %, and ε_2 is the strain at the stress level σ_2. The elastic modulus of RAC, versus the RCA replacement percentage *rr*, is shown in Figure 8. The *E* of RACI decreases gradually with *rr*, while that of RACII and RACIII initially decreases and then increases. The *E* of RACI-100 is by 32.49 % lower compared to ordinary concrete, and that of RACII-80 is by 19.45 % lower. RACIII has the lowest *E* of the three which decreases from 13.98 % to 31.72 % with an increase in *rr* from 20 % to 80 % compared to ordinary concrete. In general, elastic modulus is strongly related to concrete parameters, such as *rr* of RA in mixtures, compressive strength, and modulus of aggregate. In this context, weak properties of RA, such as cracks and higher porosity of adhering old mortar, which usually has lower modulus of elasticity, cause a decrease in the elastic modulus of RAC.

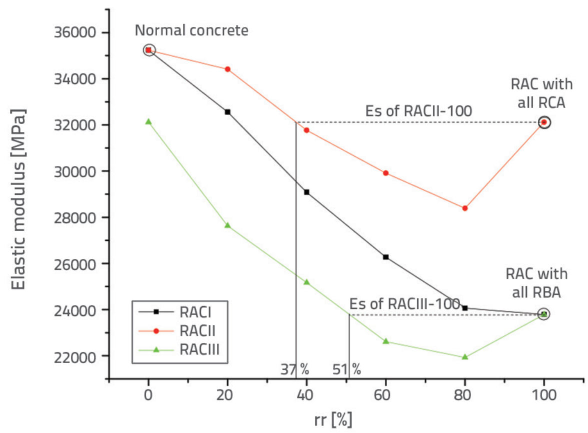


Figure 8. Elastic modulus of RACs

It can be observed from Figure 8 that the value of the elastic modulus of all RAC specimens decreases with an increase in RA content. However, there is a sudden increment of *E* with *rr* between 80 % and 100 % of RACII and RACIII. The *E* of RACII-100 is only by 8.85 % lower than that of ordinary concrete and is even higher than that of RACII with *rr* greater than 37 %. The *E* of RACIII-100 is by 25.93 % lower than that of RACIII-0 (37.77 % lower than that of ordinary concrete) and is higher than that of RACIII with *rr* greater than 51 %. Although there is no obvious turn in the curve for RACI, the *E* of RACI-100 is close to that of RACI-80, and the curve shows a certain rising trend. This means that *E* of RAC, using only one kind of RA to completely replace NA, can be higher than that of RAC using mixed RAs. Because the elastic modulus and porosity of the one kind of RA is relatively uniform, the axial compression is evenly distributed, and stress concentration is not obvious.

3.6. Relationship between elastic modulus and compressive strength

In the past, various equations have been suggested to describe relationship between the elastic modulus and compressive strength (both in MPa) of ordinary concrete according to a number of standards, as shown in Eqs. (7-11). It should be noted here that in Eqs. (8-11) a conversion factor of 0.76 from the cylinder to the cube compressive strength has been accepted as per Guo and Shi [43]).

GB/T 50010 [42]: $E_c = 10^5 / (2.2 + 34.7 / f_{cu})$ (7)

ACI 318-02 [44]: $E_c = 4127 \times f_{cu}^{0.5}$ (8)

CEB-FIP [45]: $E_c = 2.15 \times 10^4 \times (0.8 + 0.1 \times f_{cu})^{1/3}$ (9)

CSA A23.3-04 [46]: $E_c = 3951 \times f_{cu}^{0.5}$ (10)

EN 1992-1-1 [47]: $E_c = 20498 \times (f_{cu} / 10)^{0.3}$ (11)

Some other equations have also been suggested by various investigators to describe relationship between the elastic modulus and compressive strength (both in MPa) of RAC with RCA as RA. Some of these equations are given in expressions (12) to (19). Also, a conversion factor of 0.76 from the cylinder to the cube compressive strength has been accepted in Eq. (14) as per Guo and Shi [43]).

Xiao et al. [48]: $E_c = 10^5 / (2.8 + 40.1 / f_{cu})$ (12)

Dhir et al. [49]: $E_c = 370 \times f_{cu} + 13100$ (13)

Dillmann [50]: $E_c = 634.43 \times f_{cu} + 3057.6$ (14)

Mellmann [51]: $E_c = 378 \times f_{cu} + 8242$ (15)

Corindalesi [52]: $E_c = 18800 \times ((0.83 \times f_{cu})/10)^{1/3}$ (16)

Miličević et al. [53]: $E_c = 4735.7 \times f_{cu}^{0.4255}$ (17a)

$E_c = 4735.7 \times f_{cu}^{0.4255} \times (\rho / 2092)^{1.237}$ (17b)

Kakizaki et al. [54]: $E_c = 1.9 \times 10^5 \times (\rho / 2300)^{1.5} \times (f_{cu} / 2000)^{1/2}$ (18)

Zilch and Roos [55]: $E_c = 9100 \times (f_{cu} + 8)^{1/3} \times (\rho / 2400)^2$ (19)

$f_{cu} = 0.069 \times \rho - 116.1$ (20)

In Eqs. (17b), (18) and (19), the mass density of RAC can be calculated by using Eq. (20) [48]. Eqs. (7) – (19) are presented in Figure 9 for the elastic modulus versus the compressive strength of RAC. A remarkably high diversity of results can be observed. The reason for the discrepancies is quite simple: the referenced standards and authors have proposed their equations just to best fit their own experimental results. Although some of the reported results were obtained from a limited number of test specimens or limited types of RAs, the following scholars have also proved the practicability of these equations by their research results obtained in the course of research on RAC.

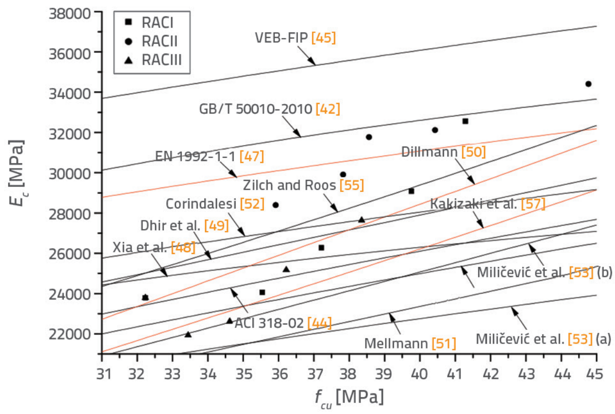


Figure 9. Various equations proposed for elastic modulus of ordinary concrete and RAC

Test results for the normalized elastic modulus of RAC (E / E_c) at the age of 28 days are presented in Table 4. It can be seen that GB/T 50010 and CEB-FIP standards overestimate the elastic modulus in comparison to experimental results, while CSA A23.3-04 underestimate the elastic modulus, and ACI 318-02 and EN 1992-1-1 usually estimate the values closer to experimental results, as shown in Table 4. The equations suggested by investigators roughly estimate the elastic modulus close to results, but the elastic modulus is underestimated in Eqs. (15) and (17a). Out of these equations, Eq. (14) has the best consistency for RACI, while Eq. (11) has the best consistency for RACII, and Eq. (8) has the best consistency for RACIII.
An alternative regression analysis for RACI was performed in this investigation based on the collected test results and Eq. (15) using the following regression equation:

$E_c = a \times f_{cu} + b$ (21)

where a and b are the regression coefficients to be determined. In order to ensure broad application of the equation, the experimental results of RAC with RBA as replaced aggregate of Yu [56] and Zhang and Zong [57] are used for reference, as shown in Figure 10.a. With a correlation coefficient $R^2 = 0.89$, the following regression coefficients are obtained: $a = 608.13$ and $b = 4744.8$. Thus, the modified relation is suggested to estimate the relation between the elastic modulus and compressive strength of RAC with RBA in Figure 10.a as follows:

$E_c = 608.13 \times f_{cu} + 4744.8$ (22)

Table 4. Normalized elastic modulus of RAC (E/E_c) according to different codes and investigators

RACs	f_{cu} [MPa]	E [MPa]	GB/T 50010	ACI 318-02	CEB-FIP	CSA A23.3-04	EN 1992-1-1	Xiao	Dhir et al.	Dillmann	Mellmann	Corindalesi	Miličević et al. (a)	Miličević et al. (b)	Kakizaki et al.	Zilch and Roos
RACI-20	41.29	32560	0.99	1.23	0.92	1.28	1.04	1.23	1.15	1.11	1.37	1.15	1.41	1.27	1.21	1.08
RACI-40	39.76	29080	0.89	1.12	0.85	1.17	0.94	1.11	1.05	1.03	1.25	1.04	1.28	1.17	1.12	0.99
RACI-60	37.21	26270	0.82	1.04	0.81	1.09	0.86	1.02	0.98	0.99	1.18	0.96	1.19	1.11	1.07	0.95
RACI-80	35.54	24060	0.76	0.98	0.77	1.02	0.80	0.95	0.92	0.94	1.11	0.89	1.11	1.05	1.02	0.90
RACI-100	32.23	23790	0.78	1.02	0.83	1.06	0.82	0.96	0.95	1.01	1.16	0.91	1.15	1.11	1.09	0.95
RACII-20	44.77	34410	1.02	1.25	0.91	1.30	1.07	1.27	1.16	1.09	1.37	1.18	1.44	1.26	1.19	1.07
RACII-40	38.56	31770	0.98	1.24	0.95	1.29	1.03	1.22	1.16	1.15	1.39	1.15	1.42	1.30	1.25	1.11
RACII-60	37.83	29910	0.93	1.18	0.91	1.23	0.98	1.15	1.10	1.11	1.33	1.09	1.35	1.24	1.20	1.06
RACII-80	35.92	28390	0.90	1.15	0.90	1.20	0.94	1.11	1.08	1.10	1.30	1.05	1.31	1.23	1.19	1.05
RACII-100	40.43	32120	0.98	1.22	0.93	1.28	1.03	1.22	1.14	1.12	1.37	1.14	1.41	1.27	1.21	1.08
RACIII-20	38.35	27630	0.86	1.08	0.83	1.13	0.90	1.06	1.01	1.01	1.22	1.00	1.24	1.14	1.09	0.97
RACIII-40	36.22	25170	0.79	1.01	0.79	1.06	0.83	0.98	0.95	0.97	1.15	0.93	1.15	1.08	1.05	0.92
RACIII-60	34.62	22610	0.72	0.93	0.74	0.97	0.76	0.89	0.87	0.90	1.06	0.85	1.06	1.00	0.98	0.86
RACIII-80	33.44	21930	0.71	0.92	0.74	0.96	0.74	0.88	0.86	0.90	1.05	0.83	1.04	1.00	0.98	0.85
RACIII-100	32.23	23790	0.78	1.02	0.83	1.06	0.82	0.96	0.95	1.01	1.16	0.91	1.15	1.11	1.09	0.95

Similarly, an alternative regression analysis for RACII was performed based on the collected test results and Eq. (11) using the following regression equation:

$$E_c = c \times (f_{cu} / 10)^{0.3} \tag{23}$$

where c are regression coefficients to be determined. In order to ensure broad application of the equation, the experimental results of RAC with RCA as replaced aggregate of Gupta et al. [58], Casuccio et al. [59], Kang et al. [60], Corinaldesi [53], Du et al. [61], and Etxeberria et al. [17] are used for reference, as shown in Figure 10.b. With a correlation coefficient R^2 = 0.86, the regression coefficient is obtained as c = 20647. Thus, the modified relation is suggested to estimate the relation between the elastic modulus and compressive strength of RAC with RCA in Figure 10.b as follows:

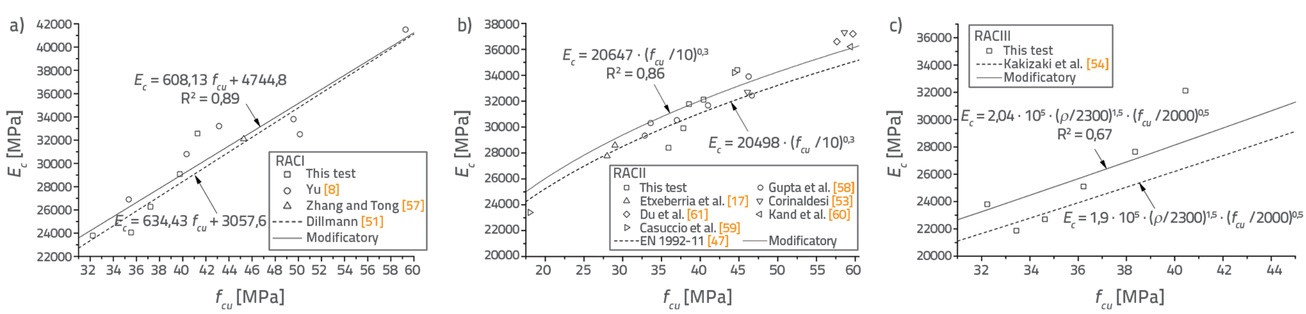
$$E_c = 20647 \times (f_{cu} / 10)^{0.3} \tag{24}$$

An alternative regression analysis for RACIII was performed based on (18) using the following regression equation:

$$E_c = d \times (\rho / 2300)^{1.5} \times (f_{cu} / 2000)^{1/2} \tag{25}$$

where c are the regression coefficients to be determined. No systematic research effort has been devoted to investigate the elastic modulus of RAC using mixed RAs, Thus, the modified relation is suggested to estimate the relation between the elastic modulus and compressive strength of RAC with RBA and RCA as mixed replaced aggregates only based on the results of this test, as shown in Figure 10(c). With a correlation coefficient R^2 = 0.67, the regression coefficients amount to d = 2. 04 × 10^5, Therefore, further investigations need to be carried out to improve the accuracy of Eq. (26):

$$E_c = 2.04 \times 10^5 \times (\rho / 2300)^{1.5} \times (f_{cu} / 2000)^{1/2} \tag{26}$$



10. Modified equations of elastic modulus of RACs: a) RACI; b) RACII; c) RACIII

4. Conclusions

Mechanical properties of RAC with RCA or RBA, and with mixed RA in particular, are systematically studied through actual experiments. Relevant conclusions are listed below:

- Compressive failure processes of RACs are similar to those of ordinary concrete. The RBA is first crushed, leading to brittle compressive failure of RACI, but there is a bonding failure between the aggregate and cement in RACII, while RACIII exhibits both of these failure modes.
- The compressive strength of RAC increases with the curing age and, in RACI and RACIII families, this strength increases rapidly at a later age. The compressive strength of RACI and RACIII first decreases gradually and then rapidly with the RBA, However, an increasing variation in the compressive strength of RACII, with 20 % or 100 % of replaced aggregate, has been noted.
- The relationship between the compressive strength and the replacement rate of RAC is studied and three equations are proposed based on Bolomey equation for three kinds of RACs.
- Stress-strain curves of RACs and ordinary concrete are basically similar in the first branch. The RCA content has a stronger influence on peak strain than the RBA content, and the elastic modulus of RACI decreases gradually with the replacement rate. But the 80 % replacement rate is the lowest point in the elastic modulus for RACII and RACIII, which decreases by 19.45 % and 37.77 % compared to ordinary concrete, respectively.
- The relationship between the elastic modulus and the compressive strength of RAC is studied. Comparison between different equations of elastic modulus and test results is presented in this investigation, then three most suitable equations are established for three kinds of RAC. Finally, necessary modifications are carried out based on experimental results, especially for RAC with mixed recycled aggregates, which is an innovative approach.

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