

Bending behavior analysis of reinforced concrete beams using recycled aggregate particles by the finite element method

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ABSTRACT

The flexural behavior of reinforced concrete beams using recycled lightweight aggregate concrete (RLWAC) is significantly influenced by the mechanical properties of the concrete and the bond mechanism between the reinforcement and the concrete. This paper presents the results of a study on the flexural behavior of RLWAC beams using the finite element method with the Response-2000 program, accounting for material characteristics and bond stress calibrated based on experimental results. The analysis was performed on RLWAC-reinforced concrete beam models with dimensions of $150 \times 200 \times 2000$ mm, using concrete with compressive strengths ranging from 12.5 MPa to 30.7 MPa (corresponding to concrete types C12/15 to C30/37) and CB400V reinforcing steel with diameters ranging from 10 mm to 25 mm. The research results showed that recycled lightweight aggregate concrete exhibits different stress-strain characteristics compared to conventional normal-weight concrete at the same compressive strength level, with the strain at peak stress of RLWAC being approximately 0.0028 (~ 0.0020 for normal-weight concrete), and the ultimate strain being approximately 0.0031 (~ 0.0035 for normal-weight concrete). The Response-2000 finite element software provides good predictions of the behavior of RLWAC beams, with the cracking moment and ultimate bending moment showing only small deviations from the experimental results (no more than 7%). The analysis results of the flexural behavior of reinforced concrete beams using Response-2000 show that, for the same concrete strength grade, increasing the reinforcement diameter can result in a difference in flexural capacity between RLWAC and conventional normal-weight concrete of up to 24%, and a difference in cracking moment of up to 55%. Conversely, for beams with the same reinforcement diameter, as the concrete strength class increases from C12/15 to C30/37, the differences in load-bearing capacity and crack resistance between the two types of concrete show a gradual decrease. Under load, the deflection of reinforced concrete beams using recycled aggregate concrete and conventional concrete differs by 1% to 26% at the time of crack formation and by 2–37% when the beam reaches its ultimate moment. The largest differences occur in reinforced concrete beams with low concrete strength grades and low reinforcement ratios.

Keywords: Recycled lightweight aggregate concrete, bond–slip relationship, crack initiation and propagation, reinforced concrete beam, finite element method, Response-2000.

INTRODUCTION

In recent years, large amounts of waste from building demolition have posed significant environmental challenges. Reusing this waste is one of the effective solutions to reduce environmental impact [1,2]. Recycled aggregate concrete (RAC), especially recycled lightweight aggregate concrete (RLWAC), is receiving considerable attention due

to its ability to conserve resources and contribute to sustainable development [3,4].

However, the use of recycled aggregates significantly alters the mechanical properties of concrete. Compared to conventional concrete, this type of concrete typically has a lower elastic modulus [5,6], higher porosity, lower compressive strength [7,8], and a weaker interfacial transition zone (ITZ) due to the presence of old mortar adhering to the aggregate

surface [9,10]. These characteristics directly affect the structural behavior of reinforced concrete elements, especially under flexural loading, by reducing stiffness and increasing deformation.

Numerous experimental studies have been conducted to evaluate the flexural behavior of reinforced concrete beams using recycled aggregates. The results show that although the ultimate load-bearing capacity may not decrease significantly, stiffness and crack resistance often decrease considerably [8,11]. However, experimental studies are often time-consuming and costly, and this often makes it difficult to fully assess the influence of various parameters such as material properties, reinforcement ratio, and loading conditions [12,13]. In addition, modern methods combining UAVs with artificial intelligence have also been applied to automatically detect and localize cracks in concrete structures [14].

For conventional concrete, the finite element method has been widely used to analyze the behavior and load-bearing capacity of reinforced concrete structures [15,16]. In particular, ANSYS has demonstrated good predictive capability for the flexural behavior, moment–deflection response, and crack development of concrete beams [17]. Finite element models using ABAQUS have also shown good agreement with experimental results in predicting the flexural behavior and load-bearing capacity of semi-precast reinforced concrete structures [18]. For concrete using recycled aggregates, some studies have also applied general finite element software such as ABAQUS, ANSYS, and DIANA [19,20]. However, because recycled concrete has high heterogeneity and its mechanical properties depend significantly on the origin and content of recycled aggregates, the old mortar layer, and the ITZ [21,22], building a finite element model often requires calibration of many nonlinear material parameters; the results may also significantly depend on the failure model and material interaction assumptions. Fully simulating the cracking process and flexural–shear behavior of the structural element significantly increases the computational effort.

To overcome these limitations, numerical analysis methods have been developed, most notably the Response-2000 program, which is based on the Modified Compression Field Theory (MCFT) [23,24]. This method allows the behavior of reinforced concrete elements to be simulated by considering the stress-strain state of concrete after cracking, including important factors such as the reduction in the compressive capacity

of concrete under transverse tensile strain, the combined action of concrete and reinforcement, and crack initiation and propagation.

In addition, Response-2000 was developed based on the MCFT framework, with assumptions consistent with CEB-FIP recommendations for describing stress-strain relationships and force transmission mechanisms [25]. The application of this model to recycled aggregate concrete is appropriate and has a solid theoretical basis.

Response-2000 can analyze the behavior of cross-sections and reinforced concrete elements under the simultaneous action of bending moment, shear force, and axial force, and provides load-deflection relationships and failure-mode predictions. Compared with traditional design methods, this method enables more accurate assessment of the influence of material factors and cross-sectional characteristics on the structure's load-bearing capacity [12,26]. In addition, Response-2000 applies the CEB-FIB crack spacing determination model, in which the average bond stress is the dominant parameter. The value of $\bar{\tau} = 1.8f_{ct}$ used in this study is in complete agreement with the CEB-FIB recommendation, thereby ensuring consistency between the analysis model and the theoretical basis [27,28].

Although numerous studies have applied Response-2000 to conventional concrete, its use for concrete with recycled aggregates, particularly for flexural behavior analysis, remains limited. In this study, the Response-2000 program was applied to analyze the flexural behavior of reinforced concrete beams using recycled aggregates. The material characteristics of the concrete were calibrated to account for those of recycled aggregate concrete, to appropriately reflect their influence on structural behavior.

The analysis results were compared with experimental data to assess the accuracy of the model. At the same time, the influence of key parameters, such as concrete strength, reinforcement ratio, and material properties, on the beam's flexural capacity was also studied.

MATERIALS AND METHODS

Experimental specimen model and material properties

This paper examines the flexural behavior of reinforced concrete beams using recycled

aggregate particles, based on beam specimens with dimensions of 150 mm in width, 200 mm in height, and 2000 mm in length. The experimental setup and loading arrangement are shown in Figure 2.

Concrete strength classes used in this study are C12/15, C16/20, C20/25, C25/30 and C30/37 (Table 1). The reinforcement is CB400V consisting of 2 steel bars with diameters varying from f10 mm to f25 mm (Table 1). The concrete materials and mix proportions use recycled lightweight aggregate particles produced from construction demolition waste according to the process of Mueller et al. (2008) [7]. The recycled aggregate particles used are classified as S2 (4–8 mm) and S3 (8–16 mm) (Figure 1). The S2 aggregate particles have a bulk density of about 430 kg/m³ and a water absorption of 28%; the S3 aggregate particles have a bulk density of 369 kg/m³ and a water absorption of 32%.

The mix designs used in the experimental study are shown in Table 2. These mixes were designed with the same water/binder ratio and target compressive strength corresponding to strength classes C16/20, C20/25, and C30/37 (denoted as M1, M2 & M3, respectively). For each concrete compressive strength class, C16/20, C20/25, and C30/37, two beam specimens were fabricated. The dry bulk density of recycled lightweight aggregate concrete ranges from 1715–1775 kg/m³.

The bond stress model used in the simulation analysis is based on the research results published by the authors [29] [30]. The formula for determining the average bond stress of recycled lightweight aggregate concrete is given by the following expression:

$$\bar{\tau} = 1.60 \sqrt{\frac{2200}{\rho_c}} f_{ct} [MPa] \quad (1)$$

In this study, the average bond stress as a function of concrete density is shown in Table 3.

It can be seen that the ratio $\bar{\tau}/f_{ct}$ of the lightweight concrete sample groups is nearly the same and can be considered constant, and this value is also similar to that proposed by CEB-FIP [27].

Finite element modeling of reinforced concrete beams using RLWAC in Response-2000

Theoretical basis

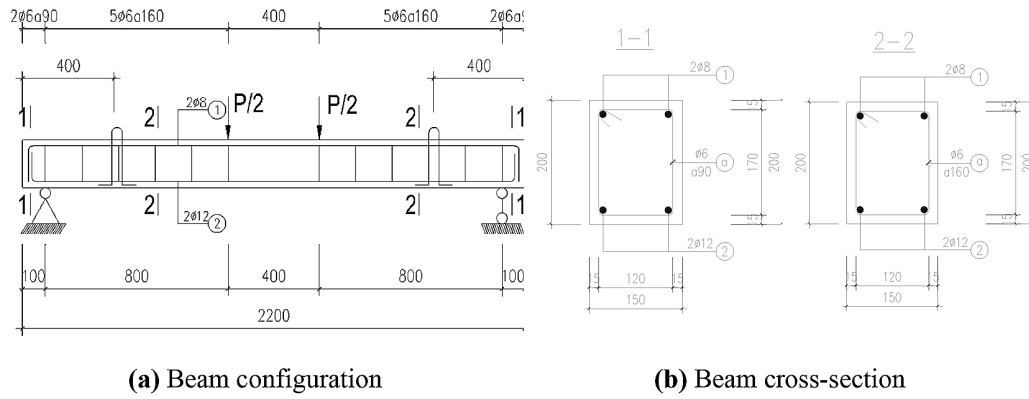
In this study, the flexural behavior of reinforced concrete beams using recycled aggregates was analyzed using the Response-2000 program, developed at the University of Toronto by Evan C. Bentz, based on the Modified Compression Field



Figure 1. Recycled aggregate particles

Table 1. Parameters and characteristics of the tested beams using RLWA [29]

Parameter	Recycled lightweight aggregate concrete					Parameter	Steel				
	C12/15	C16/20	C20/25	C25/30	C30/37		f10	f12	f16	f20	f25
Concrete compressive strength, f_c (MPa)	12.5	15.11	21.11	25	30.70	Yield strength of reinforcement, f_y (MPa)	400	400	400	400	400
Concrete tensile strength, f_{ct} (MPa)	1.58	1.73	2.05	2.23	2.47	Ultimate strength of reinforcement, f_u (MPa)	570	570	570	570	570
Elastic modulus of concrete E_c (MPa)	13206	13979	15455	16259	17292	Elastic modulus of reinforcement, E_s (MPa)	200000	200000	200000	200000	200000



(c) Experimental samples and experimental layout

Figure 2. Test setup of the RLWAC reinforced concrete beam

Table 2. Concrete mix proportions and bulk density of recycled lightweight aggregate concrete

ID	Water-to-binder ratio, W/B	Recycled lightweight aggregate ratio in concrete, V_{RA}/V_c	Sand-to-recycled lightweight aggregate ratio, V_s/V_{RA}	Fly ash-to-binder ratio, FA/B (%)	Superplasticizer-to-binder ratio, SP/B (%)	Fresh density (kg/m ³)	Coefficient of variation	Dry density, (kg/m ³)	Coefficient of variation
M3	0.36	0.35	0.45	27.61%	1%	1798	0.012	1775	0.016
M2	0.36	0.31	0.45	27.61%	1%	1783	0.011	1762	0.019
M1	0.36	0.28	0.45	27.61%	1%	1773	0.023	1715	0.047

Table 3. Average bond stress $\bar{\tau}$ as a function of concrete density

No	Concrete density ρ_c (kg/m ³)	Average bond stress $\bar{\tau}$ (MPa)
M1	1684	$1.82 f_{ct}$
M2	1746	$1.79 f_{ct}$
M3	1772	$1.78 f_{ct}$
Average		$1.80 f_{ct}$

Theory (MCFT) proposed by Vecchio and Collins [24]. The Response-2000 program allows for the simulation and analysis of linear and nonlinear structural behavior under the action of loads.

The software is developed based on the modified compression field theory (MCFT) [31]. The theory originates from the Compression Field

Theory of 1978 [26], and the Diagonal Compression Field Theory developed in 1974 [32]. This theory is based on a truss model with members inclined at 45°[24].

Methods for evaluating the shear capacity of concrete strips subjected to inclined compression between cracks are referred to as Compression

Field Theory (CFT). The fundamental problem in Compression Field Theory is determining the angle of inclination θ . This theory [24] is a development of CFT, taking into account the influence of tensile stress in the cracked concrete region. It is built on the assumption that cracked concrete can be viewed as a continuous medium with evenly distributed cracks capable of rotating in the direction of the principal stresses. The theory is based on three conditions: equilibrium, strain compatibility, and material relationships. In this approach, stress and strain are considered as average values, allowing the behavior of cracked concrete to be described without modeling each individual crack. An important feature of theory is its consideration of the reduction in compressive strength due to transverse tension, which is particularly suitable for concrete containing recycled aggregates, where the ITZ is often weaker. Response-2000 applies the crack spacing determination model according to CEB-FIP [27], in which the average bond stress is the dominant parameter. The value $\bar{\tau} = 1.8f_{ct}$ used in this study is in complete agreement with the CEB-FIP recommendation, thereby ensuring consistency between the analysis model and the theoretical basis.

Material model

For concrete, the characteristics considered include f'_c , f_p , E_c , and the stress-strain relationship. According to the published experimental research results [29], [30] the stress-strain relationship model of the concrete material is shown in Figure 3. In the case of LWAC, a stress-strain relationship model consisting of two straight-line segments is proposed. In the elastic stage of the concrete, the strain corresponding to the peak stress reaches $\epsilon_{c2} \approx 0.0028$, and the ultimate strain is $\epsilon_{cu3} \approx 0.0031$.

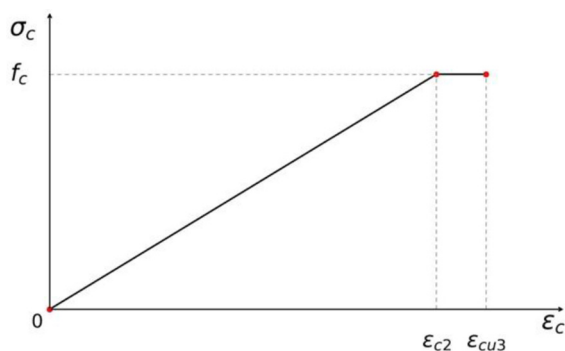


Figure 3. Concrete stress-strain relationship model

For reinforcing steel, the characteristics considered are f_y , E_s . For a conservative approach, the ideal elastic-plastic model is used (Figure 4).

The Response-2000 software was used to simulate the flexural behavior of reinforced concrete beams using LWAC.

RESULTS AND DISCUSSION

Analysis of the load-deflection relationship of recycled lightweight aggregate concrete beams based on experimental results and Response-2000 simulations

The load-deflection relationship of RLWAC-reinforced concrete beams was evaluated by comparing experimental and simulation results obtained using Response-2000 (Figure 5). The studied beams M1-f12, M2-f12, and M3-f12 have rectangular cross-sections and are singly reinforced, as shown in Figure 2. They correspond to three concrete mixes, M1, M2, and M3, with strength grades C16/20, C20/25, and C30/37, respectively. All beams use longitudinal reinforcement with a diameter of f12. The input parameters of the model are summarized in Table 1 and Figure 2. In addition, to provide further comparison and evaluate the reliability of the model, the RCA-F-7-1 and RCA-F-6-1 beam using recycled aggregate concrete from the study by Mahdi Arezoumandi [9] was also included in the analysis and comparison. The input parameters are shown in Table 4 and Table 5.

The transverse reinforcement used in the experiment [9] consisted of f10 steel bars with $f_y = 494$ MPa, $f_u = 746$ MPa, and $E_s = 206,890$ MPa.

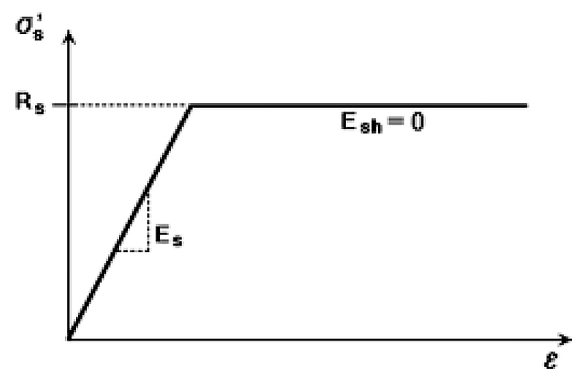


Figure 4. Reinforcing steel stress-strain relationship model

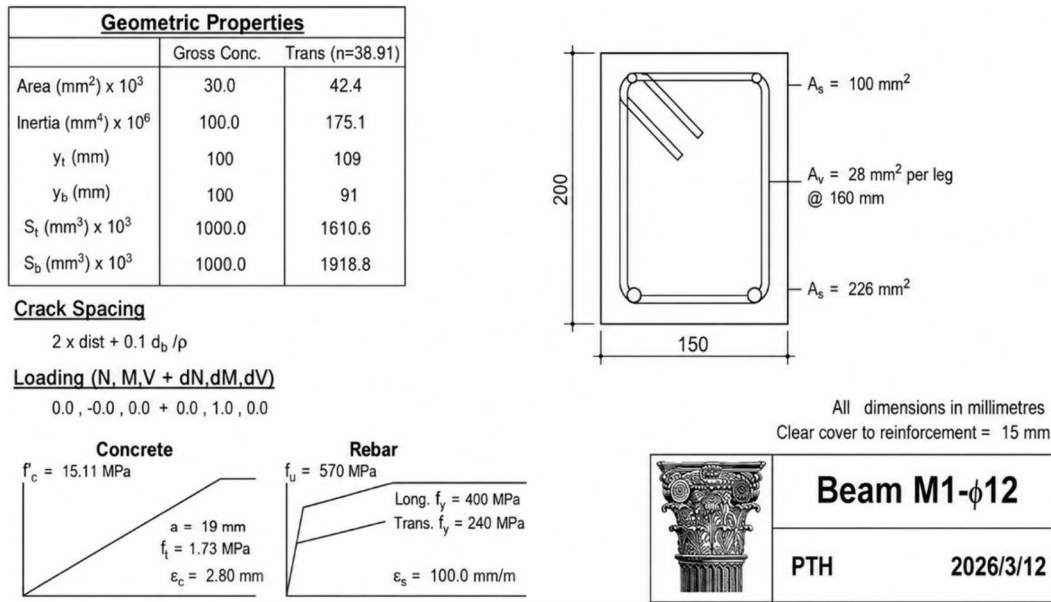


Figure 5. Presents the input data for the concrete and reinforcing steel, respectively, for the reinforced concrete beam using RLWAC

The comparison focuses on parameters characterizing the beam's flexural behavior, including the cracking moment (M_{cr}), the ultimate moment (M_u), and the mid-span deflection corresponding to these states. The results are shown in Table 6, Table 7, and Figure 6.

Comparison results between numerical simulations using Response-2000 and experimental results show that the prediction of the characteristic parameters of RLWAC beams is quite good, especially for the cracking moment M_{cr} and the ultimate moment M_u . Specifically, for M_{cr} , differences between the simulation and experimental results for the RLWAC beams (M1-f12, M2-f12, and M3-f12) are (+2%), (-4%), and (-2%), respectively, with absolute differences ranging from 2% to 4%. For the control beam RCA-F-7-1 and RCA-6-1, the M_{cr} value predicted by Response-2000 are approximately 5% and -3.4% lower than the experimental result, respectively. The deflection at the time of crack formation for the three RLWAC beams shows deviations of (+4%), (+5%), and (+4%), respectively, while the deviation for the

RCA-F-7-1 and RCA-F-6-1 beams is (-4.6%) and (-5%). These results indicate that Response-2000 can simulate the initial stiffness and behavior of the beams with reasonable accuracy before and at the time of first crack formation.

For the ultimate moment M_u , the differences between the simulation and experimental results for beams M1-f12, M2-f12, and M3-f12 are (+7%), (+1%), and (+7%), respectively. Thus, the absolute differences range from 1% to 7%, and the simulation results are consistently higher than the experimental results. For beam RCA-F-7-1 and RCA-F-6-1, the ultimate moment predicted by Response-2000 are approximately 3% and 1.5% higher than the experimental result, respectively. This result shows that the model has a fairly good ability to predict the ultimate flexural capacity of both the RLWAC beams in the study and the reinforced concrete beam using recycled aggregate concrete selected for verification.

At the limit state, the mid-span deflections predicted by Response-2000 for beams M1-f12, M2-f12, and M3-f12 are approximately 4%, 3%,

Table 4. Parameters of the RCA-F-7-1 and RCA-F-6-1 reinforced concrete beam and concrete material used in the study by Mahdi Arezoumandi [9]

Specimen	Section		Concrete		
	b (mm)	h (mm)	f'_c (MPa)	f_{ct} (MPa)	E_c (MPa)
RCA-F-7-1 & RCA-F-6-1	300	460	30.5	1.89	26300

Table 5. Parameters of the reinforcing steel used in the RCA-F-7-1 and RCA-F-6-1 reinforced concrete beam in the study by Mahdi Arezoumandi [9]

Specimen	Steel						
	Longitudinal, top	Longitudinal, bottom	Transverse	A_s (mm ²)	Yield strength, f_y (MPa)	Ultimate strength, f_u (MPa)	E_s (MPa)
RCA-F-7-1	2f13	2f22	10	380	517	791	193140
RCA-F-6-1	2f13	2f19	10	132	568	811	196570

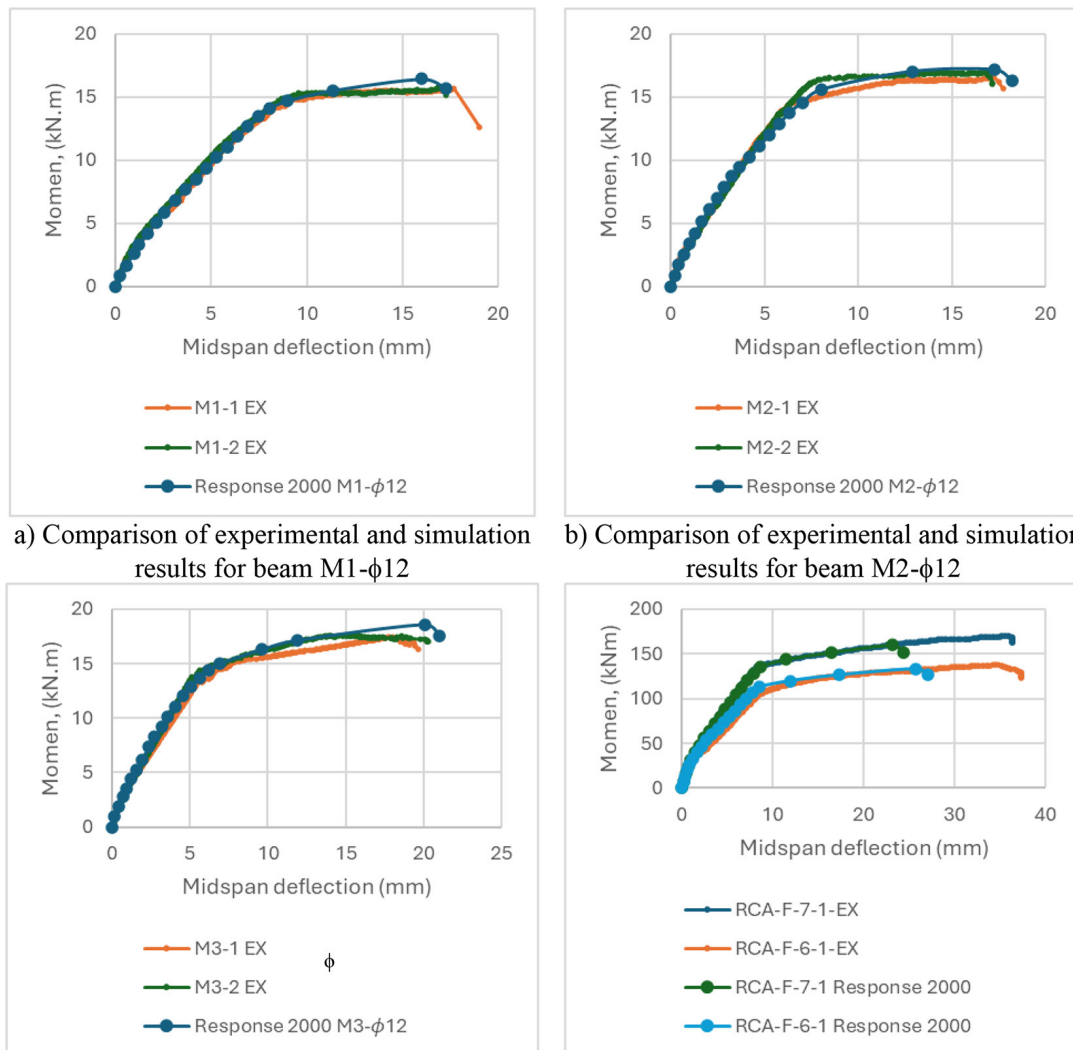


Figure 6. Comparison of experimental and numerical simulation results for the analyzed beams

and 3% higher than the experimental results, respectively. Conversely, for beam RCA-F-7-1 and RCA-F-6-1, the simulated deflection are approximately 4% and 1.9% lower than the experimental result, respectively. Overall, the absolute deflection differences at the limit state range from 1.9% to 4%, indicating that the model is able to reproduce relatively well the stiffness degradation and deformation of the beam in the post-cracking stage.

From the above results, it can be seen that Response-2000 is a suitable tool for predicting the load-bearing capacity and flexural behavior trends of recycled lightweight aggregate concrete beams. The model yields results that are relatively close to the experimental values in both the crack initiation state and the limit state, with the maximum absolute deviation not exceeding 7%.

The influence of concrete strength and reinforcing steel diameter on the load-bearing

Table 6. Comparison of M_{cr} and corresponding deflections obtained from experimental tests and numerical simulations for beams M1, M2, M3; RCA-F-7-1 and RCA-F-6-1 from the study by Mahdi Arezoumandi [9]

N _o	Beam	M_{cr} - (KNm)		Difference	Deflection (mm)		Difference
		Response 2000	Experimental results		Response 2000	Experimental results	
1	M1- ϕ 12	2.06	2.02	2%	1.44	1.39	4%
2	M2- ϕ 12	2.54	2.64	-4%	1.36	1.29	5%
3	M3- ϕ 12	3.15	3.22	-2%	0.96	0.92	4%
4	RCA-F-7-1	40.9	42	-5%	1.45	1.52	- 4.6 %
5	RCA-F-6-1	33.2	34.6	-3.4%	1.29	1.36	-5 %

Table 7. Comparison of M_u and corresponding deflections obtained from experimental tests and numerical simulations for beams M1, M2, M3 and RCA-F-7-1 from the study by Mahdi Arezoumandi [9]

N _o	Beam	M_u (KNm)		Difference	Deflection (mm)		Difference
		Response 2000	Experimental results		Response 2000	Experimental results	
1	M1- ϕ 12	16.49	15.40	7%	17.28	16.60	4%
2	M2- ϕ 12	17.15	16.91	1%	18.28	17.72	3%
3	M3- ϕ 12	18.79	17.55	7%	20.06	19.52	3%
4	RCA-F-7-1	177.9	172.6	3%	34.15	35.59	-4%
5	RCA-F-6-1	151.9	149.6	1.5%	29.75	30.33	-1.9%

capacity of recycled lightweight aggregate concrete beams

The study was conducted on reinforced concrete beams using recycled lightweight aggregate concrete with strength grades C12/15, C16/20, C20/25, C25/30, and C30/37, combined with varying reinforcement diameters of ϕ 10, ϕ 12, ϕ 16, ϕ 20, and ϕ 25. The input parameters are presented in Table 1, the beam model under two-point loading is shown in Figure 2 and the material parameters of recycled lightweight aggregate concrete and reinforcement are shown in

Figure 3 and Figure 4. Simultaneously, a comparative analysis was conducted for reinforced concrete beams using normal-weight concrete with the same strength classes and mechanical properties, as shown in Table 8.

For normal-weight concrete, the characteristics considered include f'_c , f_p , E_c , and the stress-strain relationship according to Eurocode 2 (EC2) [28]. The stress-strain relationship model of normal-weight concrete consists of two straight-line segments, as shown in Figure 3. For normal-weight concrete, in the elastic stage, the strain corresponding to the peak stress is $\epsilon_{c2} \approx 0.002$, and the ultimate strain is $\epsilon_{cu3} \approx 0.0035$. It can be seen that for recycled aggregate concrete within the scope of this study, in the elastic stage, the strain

corresponding to the peak stress ($\epsilon_{c2} \approx 0.0028$) is higher than that of normal-weight concrete ($\epsilon_{c2-NC} \approx 0.002$). At the same time, the ultimate strain of recycled aggregate concrete ($\epsilon_{cu3-RLWAC} \approx 0.0031$) is lower than that of normal-weight concrete ($\epsilon_{cu3-NC} \approx 0.0035$) [29, 30].

The predicted cracking moment (M_{cr}), corresponding deflection, and ultimate moment (M_u) and corresponding deflection of the beams were determined through numerical simulation using Response-2000 and are summarized in Table 9.

Based on the numerical simulation results in Table 9 and Table 10, it can be seen that, for the same concrete strength class, a comparison between recycled lightweight aggregate concrete and normal-weight concrete shows that, as the reinforcement diameter increases, the difference in load-bearing capacity can reach up to 24%, while the difference in crack resistance can reach up to 55%.

When using the same reinforcement diameter, as the concrete strength class changes from C12/15 to C30/37, the difference between recycled lightweight aggregate concrete and normal-weight concrete tends to decrease (for beams with ϕ 10 reinforcement, the difference in M_{cr} decreases from 30% to 19%, and the difference in M_u decreases from 4% to 2%; for beams with ϕ 12 reinforcement, the difference in M_{cr} decreases from 31% to 20%;

Table 8. Parameters and characteristics of the simulated RC beams (normal-weight concrete)

Parameter	Normal-weight concrete				
	C12/15	C16/20	C20/25	C25/30	C30/37
Concrete compressive strength, f_c (MPa)	12.5	15.10	21.10	25	30.7
Concrete tensile strength, f_{ct} (MPa)	1.6	1.8	2.2	2.6	2.9
Elastic modulus of concrete, E_b (MPa)	27287	28245	29962	31476	32837

Table 9. Predicted cracking moments and corresponding deflections obtained from Response-2000 numerical simulations for recycled lightweight aggregate concrete and normal-weight concrete

N _o	Concrete strength class	Reinforcement diameter, ϕ	M _{cr} (KNm)		Difference	Deflection (mm)		Difference
			RLWAC	NC		RLWAC	NC	
1	C12/15	10	1.51	1.97	30%	1.27	1.31	3%
2	C12/15	12	2.00	2.63	31%	1.54	1.69	9%
3	C12/15	16	2.72	3.93	45%	1.64	1.95	19%
4	C12/15	20	2.77	4.16	50%	1.70	2.08	23%
5	C12/15	25	2.92	4.53	55%	1.85	2.33	26%
6	C16/20	10	1.54	1.98	29%	1.16	1.18	2%
7	C16/20	12	2.06	2.65	29%	1.44	1.55	8%
8	C16/20	16	3.01	4.10	36%	1.60	1.89	18%
9	C16/20	20	3.18	4.60	44%	1.68	2.02	20%
10	C16/20	25	3.26	4.86	49%	1.77	2.18	23%
11	C20/25	10	1.58	2.00	26%	0.99	1.01	2%
12	C20/25	12	2.54	3.21	26%	1.36	1.44	6%
13	C20/25	16	3.25	4.28	32%	1.58	1.85	17%
14	C20/25	20	3.81	5.21	37%	1.64	1.95	19%
15	C20/25	25	3.98	5.54	39%	1.73	2.09	21%
16	C25/30	10	1.61	2.01	25%	0.83	0.84	1%
17	C25/30	12	2.61	3.29	26%	1.15	1.20	4%
18	C25/30	16	3.38	4.33	28%	1.57	1.71	9%
19	C25/30	20	4.29	5.61	31%	1.60	1.82	14%
20	C25/30	25	4.53	6.05	34%	1.70	1.97	16%
21	C30/37	10	1.98	2.36	19%	0.79	0.80	1%
22	C30/37	12	3.15	3.79	20%	0.96	0.98	2%
23	C30/37	16	3.50	4.44	27%	1.46	1.53	5%
24	C30/37	20	4.53	5.86	29%	1.59	1.76	11%
25	C30/37	25	4.83	6.32	31%	1.66	1.88	14%

and the difference in M_u decreases from 5% to 2%; for beams with $\phi 16$ reinforcement, the difference in M_{cr} decreases from 45% to 27%, and the difference in M_u decreases from 16% to 4%; for beams with $\phi 20$ reinforcement, the difference in M_{cr} decreases from 50% to 29%; and the difference in M_u decreases from 22% to 5%; and for beams with $\phi 25$ reinforcement, the difference in M_{cr} decreases from 55% to 31%, and the difference in M_u decreases from 24% to 7%). In addition, the largest difference between recycled lightweight aggregate

concrete and normal-weight concrete occurs when the concrete has a low strength class and a large reinforcement diameter (for the C12/15 concrete beam with $\phi 25$ reinforcement, the difference in M_{cr} is 55% and the difference in M_u is 24%).

Regarding the mid-span deflection trends between recycled lightweight aggregate concrete (RLWAC) beams and normal-weight concrete (NC) beams, there are clear differences. At the cracking moment M_{cr} , the deflection difference between RLWAC and NC beams is relatively

Table 10. Predicted ultimate moments and corresponding deflections obtained from Response-2000 numerical simulations for recycled lightweight aggregate concrete and normal-weight concrete

N _o	Concrete strength class	Reinforcement diameter, ϕ	M _u (KNm)		Difference	Deflection (mm)		Difference
			RLWAC	NC		RLWAC	NC	
1	C12/15	10	12.09	12.60	4%	19.67	27.01	37%
2	C12/15	12	16.01	16.83	5%	14.41	19.26	34%
3	C12/15	16	21.74	25.19	16%	11.02	12.79	16%
4	C12/15	20	22.17	26.97	22%	9.37	10.61	13%
5	C12/15	25	23.36	29.01	24%	9.13	9.66	6%
6	C16/20	10	12.32	12.72	3%	20.73	27.98	35%
7	C16/20	12	16.49	17.23	4%	17.28	21.21	23%
8	C16/20	16	24.06	26.36	10%	11.41	13.14	15%
9	C16/20	20	25.49	29.45	16%	10.05	11.15	11%
10	C16/20	25	26.12	31.23	20%	9.38	9.87	5%
11	C20/25	10	12.69	13.05	3%	23.21	28.01	21%
12	C20/25	12	17.15	17.71	3%	18.81	22.14	18%
13	C20/25	16	26.00	27.80	7%	12.35	14.08	14%
14	C20/25	20	30.52	33.14	9%	10.67	11.61	9%
15	C20/25	25	31.86	35.04	10%	9.64	9.95	3%
16	C25/30	10	13.04	13.46	3%	25.12	29.25	16%
17	C25/30	12	17.75	18.29	3%	20.22	23.02	14%
18	C25/30	16	27.07	28.81	6%	13.67	15.17	11%
19	C25/30	20	34.32	36.92	8%	11.13	12.00	8%
20	C25/30	25	35.59	38.91	9%	9.98	10.22	2%
21	C30/37	10	13.36	13.61	2%	29.29	33.52	14%
22	C30/37	12	18.79	19.08	2%	21.06	23.44	11%
23	C30/37	16	28.02	29.08	4%	14.41	15.69	9%
24	C30/37	20	35.82	37.71	5%	11.66	12.26	5%
25	C30/37	25	38.08	40.57	7%	10.58	10.79	2%

small, mainly ranging from 1% to 26%. As the reinforcement diameter increases, the difference tends to increase gradually, especially at lower strength grades (C12/15 and C16/20). At the ultimate moment M_u , the difference in deflection becomes more pronounced. Specifically, the difference can reach 35–37% for beams with low strength grades (C12/15 and C16/20) and a small reinforcement diameter ($\phi 10$).

When considering concrete strength grades, with the same reinforcement diameter, as the strength increases from C12/15 to C30/37, the difference in deflection between RLWAC and NC tends to decrease gradually (for example, for beams with $\phi 10$ reinforcement, the deflection difference at M_u decreases from 37% to 14%; similarly, for $\phi 12$, it decreases from 34% to 11%, and for $\phi 25$, it decreases from 6% to 2%). Furthermore, it can be seen that the largest difference in deflection at M_{cr} occurs for low-strength concrete

combined with a large reinforcement diameter (for the C12/15 concrete beam with $\phi 25$ reinforcement, the corresponding deflection at M_{cr} differs by 26%), whereas the largest difference in deflection at M_u occurs for low-strength concrete combined with the smallest reinforcement diameter (for the C12/15 concrete beam with $\phi 10$ reinforcement, the deflection at M_u differs by 37%).

Based on the research results presented in Table 9 and Table 10, reinforced concrete beams incorporating recycled aggregates exhibit earlier cracking and reach the ultimate moment (M_u) earlier than conventional reinforced concrete beams.

Within the scope of this study, the authors considered only reinforced concrete beams with dimensions of $150 \times 200 \times 2200$ mm, simply supported and subjected to two concentrated loads. The recycled aggregate concrete strength classes ranged from C12/15 to C30/37, while the reinforcing bar diameters ranged from $\phi 10$ to $\phi 25$,

with a yield strength of $f_y = 400$ and an ultimate tensile strength of $f_u = 570$ MPa. To extend the applicability of the research findings, future studies will investigate a wider range of parameters.

CONCLUSIONS

Based on the experimental and numerical simulation results obtained using Response-2000, the following conclusions can be drawn:

- The material characteristics of recycled lightweight aggregate concrete within the scope of this study differ significantly from those of normal-weight concrete. For recycled lightweight aggregate concrete, the strain at peak stress ($\epsilon_{cu2-RLWAC} \approx 0.0028$) is higher than that of normal-weight concrete ($\epsilon_{c2-NC} \approx 0.002$). At the same time, the ultimate strain of recycled lightweight aggregate concrete ($\epsilon_{cu3-RLWAC} \approx 0.0031$) is lower than that of normal-weight concrete ($\epsilon_{cu3-NC} \approx 0.0035$).
- According to the research results, the ratio $\bar{\tau}/f_{ct}$ of the concrete sample groups using recycled aggregates is nearly the same and can be considered a constant. This value is also consistent with the value proposed by CEB-FIP and applied in the numerical simulation using Response-2000. The use of the finite element method to analyze recycled lightweight aggregate concrete beams yields results consistent with the experimental results.
- When using the same concrete strength class, a comparison between recycled lightweight aggregate concrete and normal-weight concrete shows that: as the reinforcement diameter increases, the difference in load-bearing capacity can reach up to 24%, while the difference in crack resistance can reach up to 55%.
- When using the same reinforcement diameter, as the concrete strength class changes from C12/15 to C30/37, the difference between recycled lightweight aggregate concrete and normal-weight concrete tends to decrease.
- At the cracking moment M_{cr} , the deflection difference between RLWAC and NC beams is relatively small, mainly ranging from 1% to 26%. As the reinforcement diameter increases, the difference tends to increase gradually, particularly at lower concrete strength classes. At the ultimate moment M_u , the difference in deflection becomes more pronounced. Specifically, the difference can reach 35–37% for beams with low

strength classes (C12/15 and C16/20) and a small reinforcement diameter ($\phi 10$).

- When considering concrete strength classes, with the same reinforcement diameter, as the strength increases from C12/15 to C30/37, the difference in deflection between RLWAC and NC tends to decrease gradually. Furthermore, it can be seen that the largest difference in deflection at the M_{cr} point occurs for low-strength concrete combined with a large reinforcement diameter, whereas the largest difference in deflection at the M_u point occurs in the case of low-strength concrete combined with the smallest reinforcement diameter.
- Reinforced concrete beams incorporating recycled aggregates exhibit earlier cracking and reach the ultimate moment (M_u) earlier than conventional reinforced concrete beams.

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