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MECHANICAL PROPERTIES AND FLEXURAL BEHAVIOUR OF REINFORCED CONCRETE BEAMS CONTAINING RECYCLED CONCRETE AGGREGATE

Key words: normal aggregate (NA), recycled concrete aggregate (RCA), reinforced concrete (RC), interfacial transition zone (ITZ)

Introduction

Construction and demolition (C&D) waste is one of the most solid types of waste to accumulate annually in large quantities, because it has high durability, does not break down or decompose naturally, and thus becomes an internationally growing pollution problem with every passing year. Sweden, for example, annually produces about 1.5 M t of construction waste (Karlssan, 1998) while Poland produces 3.5 M t. One of the methods currently used to recycle this waste is to use it to replace natural aggregates, to produce new concrete by breaking clean blocks that do not contain wood, rebar, or gypsum product residues, into sizes similar to gravel granules, and then washing and staging them, i.e. separating them using sieves into different sizes. It is called recycled concrete aggregate (RCA) and has the properties of the concrete from which it was produced and contains the same components (Bołtryk, Małaszkiewicz & Pawluczyk, 2007). Choosing a well-recycled aggregate source can improve the properties of fresh concrete. Unlike natural aggregate (NA), recycled aggregate contains a large number of micro--cracks as a result of the crushing process. In addition, it may have old mortar attached to its surface. This means that an interfacial transition zone (ITZ) may form between the old mortar and the original aggregate, as shown in Figure 1, which is a weak region in RCA. That is why the quality of recycled aggregate is low.

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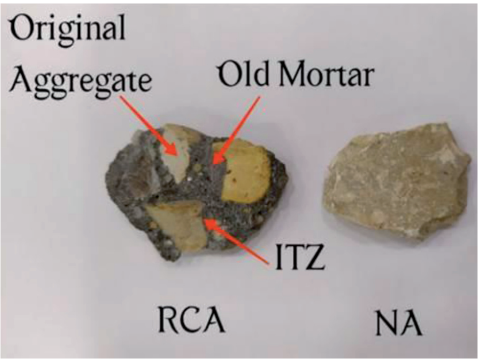

FIGURE 1. The difference between the natural and recycled aggregate

This paper explores the effect of RCA replacement ratio on the mechanical properties and flexural behaviour of reinforced concrete (RC) beams using RCA. Throughout the work, various RCA replacement levels and reinforcement ratios were used. Xiao, Li, Fan and Huang (2012) reported that changes in compressive strength are mostly a function of RCA quality, which may result in a variety of compressive strength results, including no change, a decrease in strength, or even an increase in strength in comparison to reference specimens. However, it is mostly reported that a reduction in water-to--cement ratio and an increase in cementation material content increases RCA's compressive strength. Meddah, Al-Harthy and Ismail (2020) indicated that the adoption of RCA as a partial or total replacement for NA has decreased the flexural strength of concrete. The reduction in flexural strength of RCA--concrete relates to the weakened bonding strength between the aggregate fraction and cement paste. The weakness of ITZ is significantly related to the characteristics of RCA. The bonding strength between the aggregate and cement paste is significantly weakened due to the porosity and poor strength of the old mortar found in the RCA. Yang, Park, Kim and Lee (2020) investigated the flexural behaviour of concrete beams based on RCA. The RCA contents were 30%, 50% and 100%, and tensile rebar ratios were 0.50%, 0.79% and 1.14%. The results of the tests showed that the number of cracks was greater in the RCA beams than in the NA beams. Consequently, the cracking pattern showed that the RCA beams had, in general, closer crack spacing than the NC beams. Flexural strength values of RCA beams with low reinforcement bar ratios of 0.50% and 0.79% decreased significantly as the RCA content increased. On the other hand, the influence of RCA content on the flexural strength of beams with a high reinforcement bar ratio of 1.14% was not noticeable. Moreover, the RCA content had no noticeable effect on the ductility index. The ductility of the RCA beams increased as the RCA content increased.

The purpose of this study is to assess the mechanical properties of plain concrete by partial replacement with RCA 30%, 50% and 70% by weight, and the flexural performance of RCA beams. The effect of the RCA ratio on compressive, splitting, and flexural strengths are also discussed. Both the crack patterns and load carrying capacity for RC beams are given.

Experimental program

The experimental work included evaluating the mechanical properties and flexural capacity as well as the behaviour of beams with natural and recycled aggregates.

Materials and concrete mix design

Cement (CEM I 42.5N), sand, NA and RCA were collected from crushed old concrete cubes, with steel being used for casting and reinforcing beam specimens throughout the current study. Table 1 shows the designed proportion ratios. The electrical mixer used throughout the work is shown in Figure 2a. The slump test was performed to measure the workability of fresh concrete, as shown in Figure 2b, conducted on fresh concrete immediately after it was taken from the mixer.

TABLE 1. Mix design proportion ratios

Concrete mix	Cement [kg·m^{-3}]	w/c	Water [kg·m^{-3}]	Fine aggregate [kg·m^{-3}]	Coarse aggregate [kg·m^{-3}]	
					NA	RCA
NC	465	0.44	204.60	645	1 095.0	–
RCA 30%	465	0.47	218.55	645	766.5	328.5
RCA 50%	465	0.49	227.85	645	547.5	547.5
RCA 70%	465	0.51	237.15	645	328.5	766.5

a b

FIGURE 2. Preparing fresh concrete: concrete mixer (a); lump test (b)

The cement used conformed to the specifications of ASTM C150/C150M (ASTM International, 2015). The coarse and fine aggregate conformed with the specifications of ASTM C33 (ASTM International, 2003). The steel reinforcement has been tested according to the ASTM A615/ /A615M standard (ASTM International, 2022). Table 2 shows the properties of the materials used.

TABLE 2. Properties of the materials

Material		Property	Value
Cement		Average compressive strength, aged 7 days [MPa]	23.8
Steel	Ø12	Yield strength [MPa]	565
		Ultimate strength [MPa]	687
	Ø10	Yield strength [MPa]	622
		Ultimate strength [MPa]	746
Sand		Sulphate (SO_3) [%]	0.498
Natural aggregate		Bulk density [g·cm^{-3}]	1.569
		Water absorption [%]	1
		Max size [mm]	19
Recycled aggregate		Bulk density [g·cm^{-3}]	1.466
		Water absorption [%]	5
		Maximum size [mm]	19

Details of the beams

The experimental program consisted of four RC beams, one of them being the control beam made from normal concrete (NC) while the other beams contained 30%, 50%

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and 70% RCA. The reinforcement details of the tested beams are shown in Figure 3. All beams were simply supported and tested under a four-point load.

Casting and curing

Three layers of concrete were cast in the mould. Each layer was compacted using an electrical vibrating table to ensure

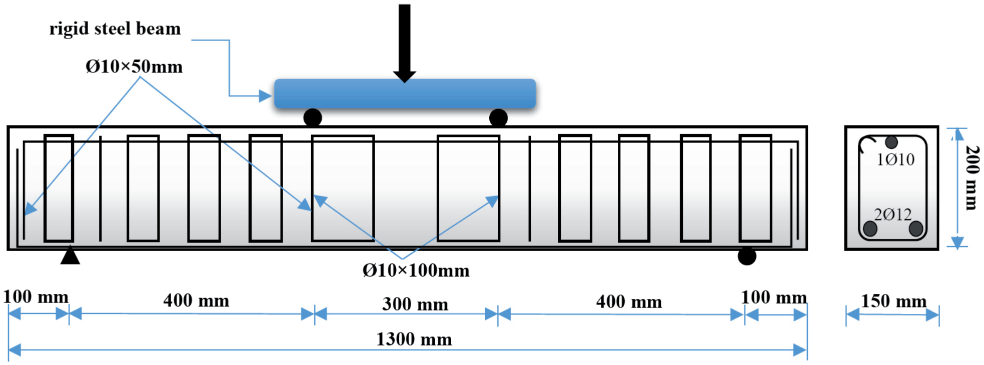

FIGURE 3. Specimen dimensions and details of steel reinforcement

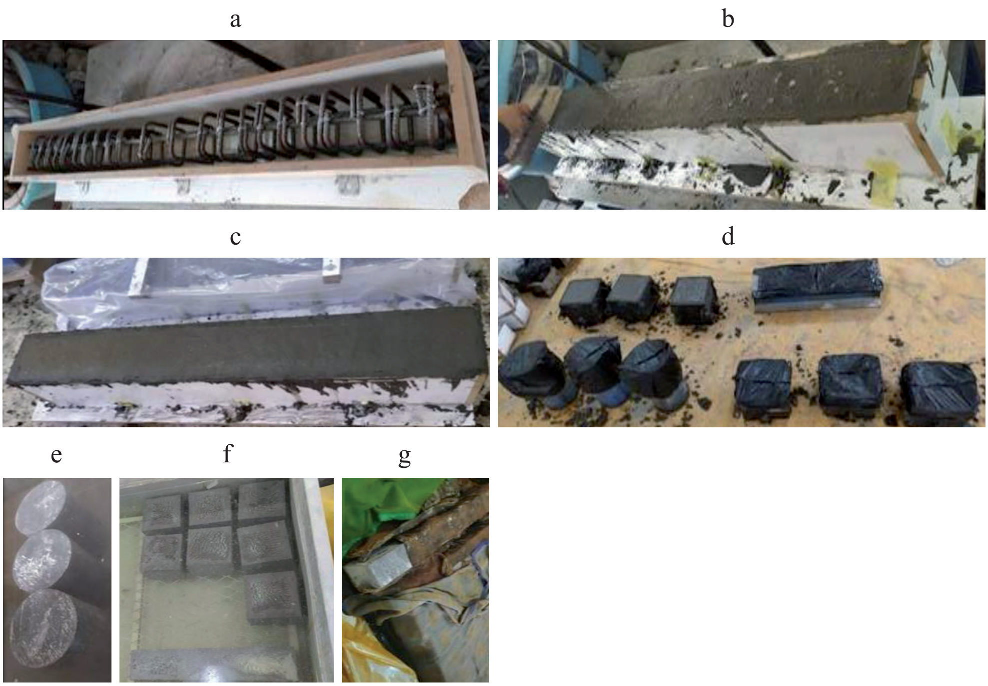

FIGURE 4. The process of casting and curing: fixing steel reinforcement in the mould (a); compacting the specimen and finishing the surface (b); covering the specimen with polyethylene sheets (c); covering the samples with polyethylene sheets (d); curing the samples in water (f–e); covering and curing of beams under wet canvas (g)

that no air was trapped inside. The top surface was smoothed by a steel trowel. Additionally, each batch included three cubes (150 × 150 × 150 mm), three standard cylinders (300 × 150 mm), and one prism (100 × 100 × 500 mm). All specimens (beams, cubes, cylinders and prisms) were covered with polyethylene sheets after casting to prevent water evaporation. After 36 h, the moulds were removed and the beams were cured in the laboratory by covering them with wet canvas until the testing age of 28 days. Figure 4 shows the process of casting and curing.

Results and discussions

This section presents and discusses the results of the cubes, cylinders and prisms, as well as flexural testing on four RC beams. The results include compressive strength, stress–strain curve, flexural strength, splitting tensile strength, crack pattern, failure mode, load capacity and mid-span deflection for each of the tested beams.

Properties of fresh concrete (workability)

The slump results for different mixes are shown in Figure 5. It can be seen that as the replacement ratio of RCA increased, the slump value of RCA fresh concrete decreased by 26.3%, 42.1% and 57.9% for RCA 30%, 50% and 70% respectively, compared to the normal concrete, due to the relatively large water absorption and rough surface of the RCA.

Mechanical properties of hardened concrete

In general, it is noticeable that the mechanical properties of RCA concrete decrease in varying proportions compared to normal concrete, and this is in agreement with the results reported by Saadoon, Mashrei and Al Qumari (2022). This is because the ITZ between RCA and cement paste was weaker than that between NA and the paste. All tests were performed after 28 days of curing.

Compressive strength

Table 3 illustrates that the compressive strength of concrete cubes typically decreases with increasing the replacement ratio of RCA. The compressive strength of RCA concrete with the replacement of 30%, 50% and 70% decreased by 9.10%, 18.88% and 22.57% respectively, compared to the compressive strength of normal concrete.

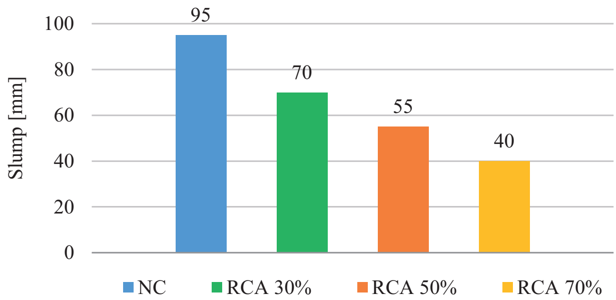

FIGURE 5. Slump results

TABLE 3. Compressive strength results for cubes

Concrete mix	Average cubic compressive strength (f_{cu}) [MPa]	Decrease in compressive strength [%]
NC	42.30	–
RCA 30%	38.45	9.10
RCA 50%	34.31	18.88
RCA 70%	32.75	22.57

Stress–strain curve

Figure 6 shows the stress–strain relations of NC and RCA mixes with RCA ratios (30%, 50% and 70%). It can be seen that the behaviour of all the specimens differed slightly throughout the first stage (linear stage) compared with normal concrete. The RCA proved to have a high strain capacity, which indicated high ductility. The maximum RCA strains ranged from 0.0056 to 0.0072, whereas the maximum NC strain was 0.0042.

Further, as can be seen from Figure 7, the cone-type failure mode in the cylinders appeared in NC and RCA concrete.

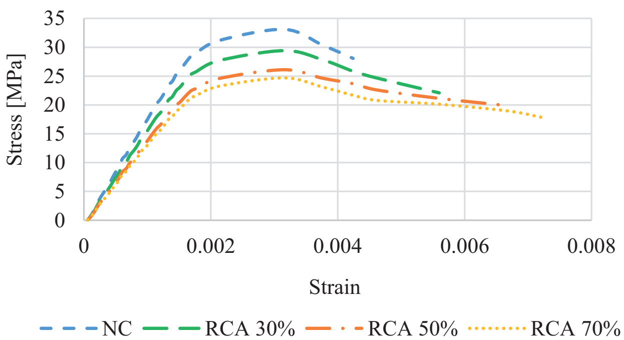

FIGURE 6. The stress–strain relations

FIGURE 7. Cylinders failure mode

Flexural strength

Concrete flexural strength is an indirect measure of tensile strength in flexure. Table 4 shows a slight decrease in the modulus of rupture compared with NC (18.83% decrease). According to Figure 8, all samples had a fracture in the middle third.

TABLE 4. Modulus of rupture (f_r)

Concrete mix	Modulus of rupture (f_r) [MPa]
NC	42.30
RCA 30%	38.45
RCA 50%	34.31
RCA 70%	32.75

FIGURE 8. Fracture position in concrete prisms

Splitting tensile strength

The tensile strength of concrete with RCA was lower, but less than that of the compressive strength, whereas the tensile strength dropped from 5.126 to 4.582 N·mm^{-2} (10.61% decrease) in comparison to the normal concrete. The reason for this was that the surface of the RCA was rough due to residual mortar that provides good bonding strength with the concrete, unlike the case where the compression behaviour was weak. Table 5 shows the experimental indirect tensile strength (f_{cr}).

TABLE 5. Indirect tensile strength (f_{cr}) cylinder concrete according to tensile load (P_t)

Concrete mix	P_t [kN]	$f_{cr} = \frac{2P}{\pi DL}$ [N·mm^{-2}]	$f_{cr} = 0.7\sqrt{f_{cu}}$ [N·mm^{-2}]
NC	362.335	5.126	4.552
RCA 30%	352.086	4.981	4.340
RCA 50%	339.009	4.796	4.100
RCA 70%	328.882	4.582	4.005

The behaviour of reinforced beams in flexural tests

Crack patterns and failure modes

The crack patterns and failure modes of the beams were investigated. As shown in Figure 9, the RCA concrete beams exhibited more cracks at the initial cracking stage than the control beam. This phenomenon could be explained by the fact that the ITZ between the RCA and paste was weaker than the ITZ between the NA and paste. The RCA concrete's weak ITZ was caused by residual mortar on the surface of the RCA. New cracks appeared inside and outside the constant bending zone in both the NA and RCA beams as the load increased after the initial cracking stage. Both types of beam failed in flexure as a result of new and present cracks propagating up to the compression zone. The number of cracks in the RCA beams, on the other hand, was greater than in the control

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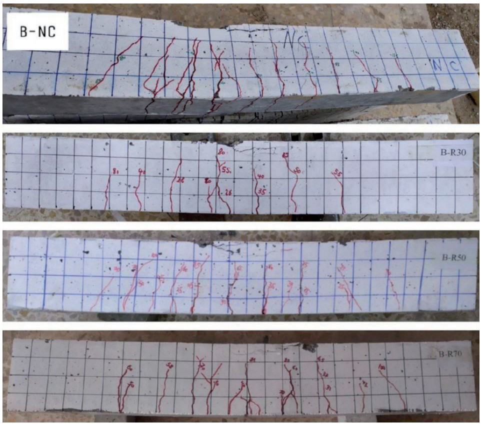

FIGURE 9. Typical crack patterns for beams

beam (B-NC). The test results revealed that tensile cracks developed first, followed by the yielding of the tensile rebar and concrete crushing, which is often identified as a tension failure. The first cracks developed on the beam's bottom face, between the loading points, where it was exposed to pure bending. The cracks became larger as they progressed toward the upper face. Additional flexural cracks occurred between the load and the supports as the load increased after the first cracking. As the applied load was increased more, most of the flexural cracks formed vertically, and slant flexure-shear cracks emerged.

Load–deflection relationships

The load–deflection curves of both NA and RCA beams are shown in Figure 10. In the initial cracking state, for all beams, the load–deflection relationships were linear and almost similar, while the deflections were proportional to the loads. It was noticeable that increasing the replacement by RCA led to reduced load-carrying capacity. The stiffness of the RCA beams decreased when the load was increased. When the load reached about 0.85–0.90% of the ultimate load, the load–deflection curves tended toward the horizontal axis. The RCA beam load–deflection curves showed greater ductility than the NC beam. It can be noted that the RCA beams had higher deflections than

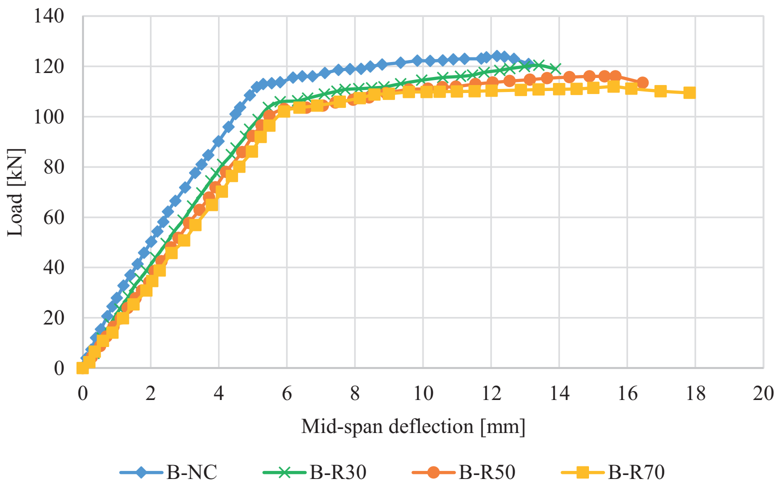

FIGURE 10. Load–deflection curve for beams

the NC beam. The increase in the deflections for beams with RCA replacement might be due to the lower modulus of elasticity of the RCA beams. Furthermore, the load values for RC beams at Δ_u = 12.17 mm for the NC beam were 124.08 kN, 118.41 kN, 113.73 kN and 110.32 kN for B-NC, B-R30, B-R50 and B-R70 respectively.

Stages of loading and displacement

Table 6 summarises the substance of the experimental results. The cracking load (P_{cr}), yield load (P_y), ultimate load (P_u), and related mid-span deflection are essential backlashes of the flexure critical beam, which are obtained from the load–deflection relation of the tested specimens.

As for beams in which 30%, 50% and 70% of the NA has been replaced by RCA, the first cracking load was a decrease by about 20.67%, 28.5% and 38.3% respectively, in comparison with beam B-NC. The lower cracking load of the RCA beams was attributed to the weaker ITZ between the cement paste than in the NA beams. Similarly, the ultimate load was a decrease by about 3.0%, 6.5% and 10.5% respectively. This implies that when the RCA content increased, the flexural ultimate strength decreased.

Conclusions

The results described here suggest the following conclusions:

1. Replacement of normal aggregates (NA) in concrete mixes by recycled concrete aggregates (RCA) caused a decrease in the compressive strength for cubes by 9.10%, 18.88% and 22.57%, and a decrease in the compressive strength for cylinders by 10.87%, 20.9% and 25.21%, for replacement ratios of 30%, 50% and 70% respectively.
2. The stress–strain curve for RCA concrete cylinders showed a high strain capacity (high ductility) in comparison to normal concrete (NC).
3. The splitting tensile strength and flexural strength of RCA concrete decreased variously with the increasing proportion of recycled aggregate (10.61% decrease).
4. The RCA concrete showed a slight decrease in the modulus of rupture compared with NC (18.83% decrease).
5. The results expressed that the RCA beams had a higher number of cracks than the normal concrete beam. As a result of the cracking pattern, the RCA beams showed mostly closer crack spacing and less width than the NC beam.

TABLE 6. Summary of the test results of the beams

Beam	Initial cracking stage		Yielding stage		Ultimate stage		Mode of failure
	P_c [kN]	Δ_{cr} [mm]	P_y [kN]	Δ_y [mm]	P_u [kN]	Δ_u [mm]	
B-NC	35.8	1.10	115.5	6.2	124.08	12.17	flexure
B-R30	28.4	1.50	106.9	6.6	120.40	13.40	flexure
B-R50	25.6	1.25	103.3	6.5	116.08	15.65	flexure
B-R70	22.1	1.00	102.9	6.8	111.14	16.12	flexure

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6. The deflection, first crack load, and ultimate load for RC beams decreased with the increasing replacement ratio of RCA.
7. The load-carrying capacity decreased by 2.96%, 6.47% and 10.42% at replacement ratios of 30%, 50% and 70% respectively.

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Summary

Mechanical properties and flexural behaviour of reinforced concrete beams containing recycled concrete aggregate. Increasing waste recycling has become an essential process in the construction industry due to the environmental and economic advantages, such as minimizing waste in landfills, saving natural resources, and decreasing pollution. Crushing and sieving waste from standard compression test cubes is used to produce the recycled concrete aggregate (RCA). A set of standard concrete cylinders, cubes, and beam specimens were made by utilizing coarse aggregate replacement ratios of 0%, 30%, 50% and 70%. At the day 28 stage, the specimens were tested to determine compressive strength, stress–strain relationship, splitting tensile strength, and flexural strength. In addition, four reinforced concrete (RC) beams were cast and tested under a four-point load to evaluate the flexural behaviour of RC beams with partial replacement of the natural aggregate with RCA. One was a natural aggregate (NA) control beam,

while the others had varying RCA ratios (30%, 50% and 70%). The results show that the compressive strength of RCA concrete with the replacement by 30%, 50% and 70% decreased by 9.10%, 18.88% and 22.57% respectively, in comparison to the compressive strength of normal concrete (NC). The RCA concrete showed a high strain capacity, which indicated high ductility. The maximum RCA type strains ranged from 0.0056 to 0.0072. Concrete flexural strength showed a slight decrease in comparison to NC (18.83% decrease), where the tensile strength showed a 10.61% decrease in comparison to NC. As for RC beams, the load-carrying capacity decreased by 10.5% with increases in the replacement ratio.