

FLEXURAL RESPONSE OF RC SLABS WITH DOSAGES OF RECYCLED AGGREGATES AND GFRP REINFORCEMENT

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Abstract

The purpose of this study is to assess the mechanical performance of structurally appropriate concrete made from natural aggregates and partially recycled aggregates. Prism, cubic, and cylinder specimens were tested for the static modulus of elasticity, density, and compressive strength as part of the experimental program. Reinforced concrete slabs containing both aggregate types and either steel or GFRP bars were subjected to full-scale bending testing. The results showed that the basic mechanical parameters of concrete were unaffected by the addition of recycled particles. Mixed with recycled materials, the compressive strength, a stiffness, and density of the resulting material were all on a par with those of conventional aggregate concrete. When combined with steel reinforcement, the recycled concrete showed deformation behavior comparable to that of natural aggregate concrete in slab tests, effectively controlled cracks, and demonstrated sufficient load-bearing capacity. In conclusion, the results show that, with proper design, recycled aggregate concrete (RAC) can be a sustainable and structurally sound alternative to conventional concrete mixes. This lends credibility to its use in contemporary building projects and shows that it can help save the environment.

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Key words

- Recycled aggregates,
- GFRP reinforcement concrete,
- Steel reinforcement concrete,
- Compressive strength,
- Flexural behavior.

1 INTRODUCTION

The substantial amount of waste generated by the extensive use of concrete in construction offers ample opportunities for recycling and reusing materials. Closed-loop recycling of concrete has been a hot topic over the past few decades (Eurostat, 2021) as a potential solution to the problems posed

by construction and demolition waste (CDW) as a bulk waste stream and to preserving the raw materials needed to make new concrete. According to Eurostat (Eurostat, 2021), the total amount of waste generated in the European Union in 2022 was over 2.2 billion tons, of which almost 38 % (858 million tons) derived from construction and demolition activities and 22.7 % (506 million tons) belonged to mining and quarrying operations (Fig. 1).

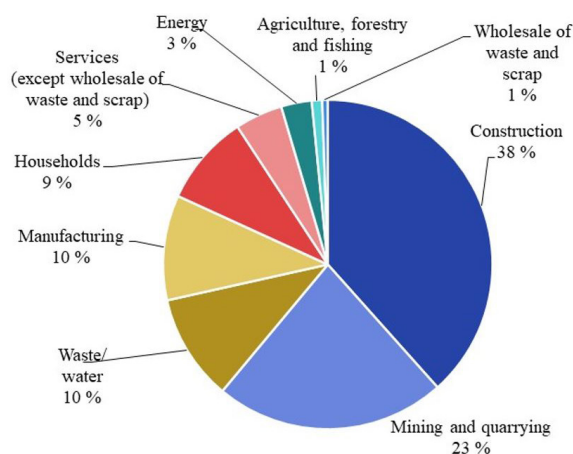


Fig. 1 Total waste generated in the European Union in 2022 according to economic activities (Eurostat, 2021)

For instance, the European standard EN 206 (STN EN 206, 2016) delineates two classifications of coarse recycled aggregate ($d < 4$ mm). It specifies that the maximum replacement of coarse natural aggregate shall not exceed 50 % by mass. Many people are interested in the closed-loop recycling of concrete, as using RCA as a component material instead of natural aggregate (NA) is one way to achieve it. By reducing the amount of CDW that ends up in landfills, this strategy accomplishes a double-win, i.e., it conserves NA and keeps it out of quarries. (Otsuki, N.; Miyazato, A. and Yodsudjai, 2003) examined how the RCA affects concrete characteristics. Research indicates a strong association between the parameters of the parent aggregate and the performance of recycled aggregate concrete (RAC). Studies have suggested that RCA has increased porosity, water absorption, and decreased density, which explains many of its strength and durability differences from natural aggregate concrete (Guo et al., 2013); (Behera et al., 2014), as well as its material variability, which may lower the strength between the mortar and aggregates in the RCA. Numerous investigations have revealed no discernible differences between RAC and NAC at replacement levels below 30% (Etcheberria, Vázquez, et al., 2007); (Evangelista & de Brito, 2007); (Etcheberria, Marí, et al., 2007), so that RAC may be more widely used. As a result, it is not uncommon for precast natural aggregate concrete (NAC) members with cast-in-place RAC components to be used in new construction, while strengthening during rehabilitation by using a RAC overlay is a common proposal for existing NAC structures. Both scenarios are likely to involve composite RAC/NAC concrete structures. The shear strength of the contact between RAC and NAC must be measured for the reasons given above. Therefore, RAC mechanical properties are affected by concrete composition and curing conditions (Ferreira, L.; De Brito, L and Barra, 2011); (Fonseca et al., 2011); (Etcheberria, Vázquez, et al., 2007), whereas surface roughness, concrete tensile strength, differential stiffness, and differential shrinkage between concrete layers primarily determine the NAC-to-NAC interface shear strength (Wall, J. W. and Shrive, 1988).

Although prior research has suggested that pre-saturating recycled aggregates before use is preferable, researchers (Ferreira et al., 2011); (González-Fontebó & Martínez-

Abella, 2007); (Padmini et al., 2009) and (Martínez-Lage et al., 2012) used the water compensation method instead to account for the higher water absorption of recycled coarse aggregates. This was because using pre-saturated aggregates slightly reduces the performance of RAC (Ferreira, L.; De Brito, L and Barra, 2011). (González-Fontebó & Martínez-Abella, 2007) examined the shear resistance of RCA and NA concrete beams reinforced with shear in static bending trials and found no variation. González-Fontebó and Martínez-Abella (González-Fontebó & Martínez-Abella, 2007) 50% substituted coarse aggregate to compare the shear performance of conventional reinforced concrete beams and recycled concrete beams. They extensively tested four beams to identify the appropriate transverse reinforcement. The RAC fractured at lower loads, while the other concrete mixes had similar deflections and load-bearing capacities. Because reinforced beams with RA have tension reinforcement splitting fissures, they suggested tighter constraints on beam stirrup spacing to solve both issues. (González-Fontebó et al., 2009) added 8% silica fume to the mixes. RAC mixes reinforced with silica fume did not show splitting cracks along the tension reinforcement, unlike the other study. However, they did not examine how the fine recycled aggregate replaced the original material.

Other criteria, including the economic and environmental performances, have been investigated in previous studies. A study by (Hollingworth, 2021) evaluated the incremental cost of RAC to NAC and found that RAC is more expensive to manufacture from recycled material. (Srour, 2012), (Begum et al., 2006), and (Tam, 2008) found that recycling concrete is cheaper than landfilling. (Duran et al., 2006) investigated how financial mechanisms can promote RCA over NA, and (Coelho & De Brito, 2013) examined the economic sustainability of RCA recycling facilities.

Given their reduced life-cycle costs, durability, maintenance costs, and longer service life (100 years) in severely corrosive environments, fiber-reinforced polymer (FRP) concrete structures are more cost-efficient than steel-reinforced ones, even though they are initially more expensive (Nishizaki et al., 2020). Nevertheless, several durability concerns with recycled aggregate prevent its wider usage. These concerns include faster carbonation and higher permeability, which threaten the passivation of steel rebars in RAC. For concrete structures exposed to harsh environments, a combination of RAC and FRP rebars, such as glass fiber reinforced polymer (GFRP), is a potentially fruitful option. As stated by Gudonis et al. (2014), GFRP is one of the most popular substitutes for steel rebars in the building sector due to its lower cost compared to other types of FRPs. According to Sagemo and Storck (Mara et al., 2013), a recent study found that steel reinforcements had fewer environmental implications, although FRP-reinforced bridges offer a minor economic advantage. To prevent deceiving conclusions, it is important to consider technical feasibility, direct life cycle costs, and environmental implications when selecting alternatives to steel reinforcements (Ilg et al., 2016); (Ramachandra Murthy et al., 2018). Scientists are very interested in the potential uses of GFRP reinforcement in RAC for building applications (Chen et al., 2021); (Raza et al., 2021); (Raza & Rafique, 2021); (Traykova, M.; Zaharieva, R. and Kerelezova, n.d.).

2 SIGNIFICANCE OF RESEARCH

Concrete slabs produced using recycled aggregates and those using natural aggregates will be compared and evaluated in this project. Eight slabs are part of the study; four have GFRP reinforcement (marked as G) and four have traditional steel reinforcement (marked as S). The purpose of the experimental program is to determine the impact of recycled concrete aggregates and the type of reinforcement on the overall structural behavior by verifying and analyzing the flexural performance of each slab type.

3 MATERIALS

3.1 Materials

3.1.1 Water and cement

Potable water, which was compliant with relevant Slovak standards for concrete production, was used to ensure the cement's hydration and the curing of concrete specimens. Portland composite cement CEM-I 42.5 R with a specific gravity of 3.15 was used as a binder in this study.



Fig. 2 Natural and recycled concrete aggregates used in this research

3.1.2 Natural and Recycled Aggregates

Experimental works included two types of aggregate: natural river aggregate (NA) with size fractions of 0-4 mm, 4-8 mm, and 8-16 mm, and recycled concrete aggregate (RCA) with 4-8 mm and 8-16 mm fractions (Fig. 2). NA is a natural type of aggregate from a Veľké Úľany (Slovakia) gravel pit, whereas the RCA was obtained from demolished concrete. In principle, the RCA had a higher water absorption than the NA due to the residual mortar (original cement paste) remaining on the surface of the original aggregate. To evaluate the effect of RCA on the basic parameters of fresh and hardened concrete, two different concrete mixtures were prepared, i.e.:

- NAC – concrete with only natural aggregates, which served as the reference mix,
- RAC – 4/16 natural aggregate fractions 4-8 and 8-16 replaced by recycled aggregates

3.1.3 Steel and GFRP reinforcement

The steel and GFRP reinforcement parameters were determined by averaging four measurements. For the steel reinforcement, the values of yield strength, ultimate tensile strength, and elastic modulus were 575.8 MPa, 675.9 MPa, and 203.2 GPa, respectively. The ultimate tensile strength and the modulus of elasticity of the GFRP bar were 860 MPa and 54.5 GPa, respectively.

3.2 Mix design

The mix design of the fresh concrete is given in Table 1. Portland cement CEM-I 42.5 R served as the binding material due to its consistent strength development and compatibility with various admixtures. To optimize the workability of the fresh mixture while minimizing the water-to-cement ratio, Stachement 2000 superplasticizer was incorporated. This high-range water-reducing admixture improved flow characteristics without compromising strength or durability. The plasticizer content was 0.07% and 0.1% by mass of cement for the NAC-100 and RAC-100-4/16, respectively. The water-cement ratio was 0.52 for all the mixes. The mix design used for this study is reported in Table 1.

The aggregates and cement were added to the gravity mixer. After thoroughly blending the dry components, half the water was added initially, and the remaining water was incorporated incrementally along with the plasticizer. The fresh concrete was obtained by combining the dry ingredients with the water and plasticizer. The total duration of mixing for each concrete batch was ten minutes during the preliminary mixing phase. Before pouring the fresh mixed concrete into molds, a slump test was performed to evaluate the workability of each mixture. Subsequently, the concrete was poured into oiled molds. Following their demolding, the concrete specimens for testing the mechanical properties and flexural response were stored in a controlled environment at 20°C and with a relative humidity exceeding 95%.

Tab. 1 Concrete mix design for 1m³ of fresh concrete – mass ratio

	NAC-100	RAC-100-4/16
Cement CEM-I 42.5 R	0.13	0.13
Water	0.07	0.07
NA 0/4	0.43	0.43
NA 4/8	0.14	-
NA 8/16	0.23	-
RA 4/8 mm	-	0.14
RA 8/16 mm	-	0.23

4 EXPERIMENTAL METHODS

4.1 Workability and mechanical properties

Slump tests according to STN EN 12350-2 (STN EN 12350-2, 2020) were used to determine the workability of all the concrete mixes. The density of the hardened concrete was

determined in accordance with STN EN 12390-7 (STN EN 12390-7, 2020). Cube specimens with edge lengths of 150 mm were cast to measure compressive strength at 28 days, according to STN EN 12390-3 (STN EN 12390-3, 2020). The rate of increase in the compressive stress during the concrete compressive-strength testing was 0.5 MPa/s. The modulus of elasticity was tested on beams measuring $100 \times 100 \times 400$ mm in accordance with STN EN 12390-13 (STN EN 12390-13, 2022) standard.

Eight RC elements with cross-sectional dimensions of 150×100 mm were prepared to evaluate the effect of the RAC content and GFRP reinforcement on the flexural behavior of the RC slabs. The slabs were divided into four main groups:

- NAC-100-S: Natural aggregate concrete and steel reinforcement
- NAC-100-G: Natural aggregate concrete and GFRP reinforcement
- RAC-100-4/16-S: Recycled aggregate concrete with replacement of 4/16 fraction by RCA and steel reinforcement
- RAC-100-4/16-G: Recycled aggregate concrete with replacement of 4/16 fraction by RCA and GFRP reinforcement

In every main group, two slabs with a span of 1.0 m were cast. The slabs were reinforced longitudinally with reinforcement $2\text{Ø}10$ mm at the bottom surfaces. Moreover, the slabs were reinforced in the transverse direction with construction steel reinforcement $\text{Ø}8$ mm to ensure the correct position of the main steel reinforcement in S-type slabs. To prevent lifting of the GFRP reinforcement in molds during the concreting, $\text{Ø}20$ mm rebars were added as ballast at the end of the reinforcement (See Fig. 3). A 20 mm concrete cover was chosen for all the main reinforcement. The geometric parameters and reinforcement of the slabs are illustrated in Fig. 4. The loading details of the slabs are illustrated in Fig. 5 and were chosen to reach a constant bending moment at the midspan of the beams tested.

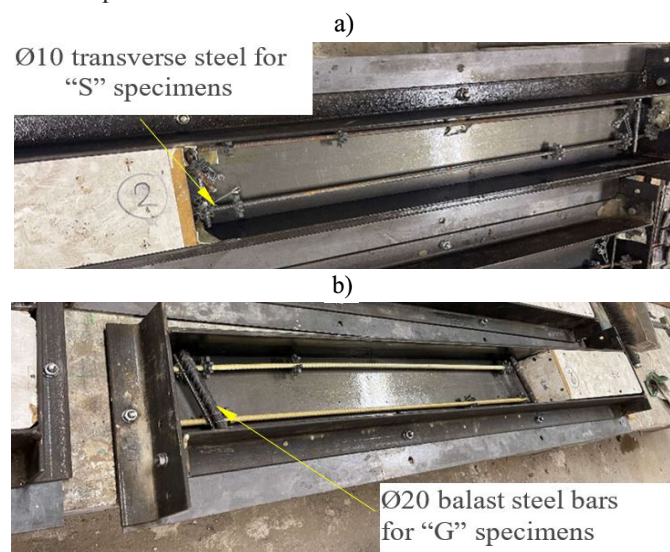


Fig. 3 Reinforcement of RC slabs in molds before casting a) steel reinforcement ("S" specimens), b) GFRP reinforcement ("G" specimens).

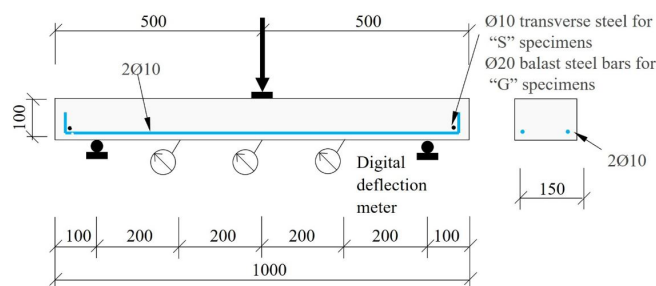


Fig. 4 Details of RC slabs - dimensions and reinforcement (all dimensions in mm)

All the slabs were tested using a 250 kN capacity servo-hydraulic actuator installed in a rigid load frame until failure under a three-point bending setup. The load application had a vertical deformation increment of $3 \mu\text{m/s}$. The slabs were supported on a roller and a pin support, 100 mm from each end. Steel plates were placed between the actuator and RC slabs to concentrate the load. Another steel plate was placed in support to transfer the reaction from the beam to the force gauges. Linear variable differential transducers (LVDTs) were placed to record the maximum deflections, i.e., one at the midspan, where the bending moment was highest, and two at a position 200 mm from the loading. The LVDT has a maximum operational range of 75 mm, which enables precise measurements of the slab's movements under a load. The crack patterns and widths were marked on the slab's surface for every step. The load gradually increased in 5 kN increments until it reached 20 kN. Then it was reduced to 2.5 kN per step until the beams eventually failed.



Fig. 5 Experimental set-up: 1 – tested slab, 2 – loading cell, 3 – roller support, 4 – LVDT sensors

5 TEST RESULTS AND DISCUSSION

5.1 Workability

Fig. 6 illustrates the average slump values measured using the standard cone test (Abrams's cone), which was based on two independent measurements for each mixture.

The data clearly demonstrates a consistent and expected trend: as the dosage of recycled aggregates increases, the workability of the fresh concrete decreases. The reference concrete mixture from the natural aggregates (NAC) exhibited

a slump of 210 mm and 200 mm for the NAC-100-S and NAC-100-G mix designs, respectively. In contrast, the concrete with the recycled aggregates exhibited much greater reductions in workability, i.e., with slump values of 30 mm and 10 mm for the RAC-100-4/16-S and RAC-100-4/16-G, respectively. These results suggest that RA impacts the workability of fresh concrete due to the consumption of the mixing water, because RA generally has a higher porosity than NA (Silva et al., 2018); (Kapoor et al., 2020); (Lavado et al., 2020).

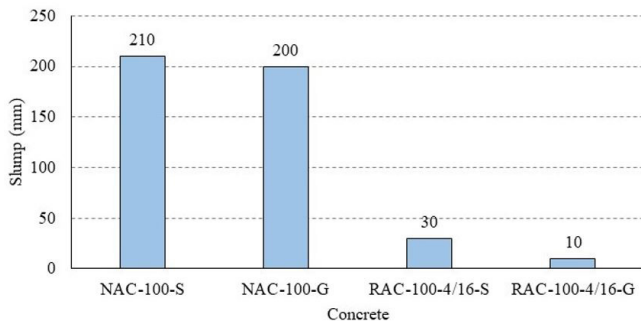


Fig. 6 Comparison of the slump tests

5.2 Density of concrete

The density of the concrete was determined as the average of three measurements of the cubes. The values of the standard deviation were 4.20, 3.89, 7.88, and 5.92 for specimens NAC-100-S, NAC-100-G, RAC-100-4/16-S, and RAC-100-4/16-G, respectively. The experimental findings on the density of the hardened concrete also indicate that adding recycled aggregate typically decreases the overall density of the concrete mixtures (Fig. 7). This observation aligns with our expectations, as RA has a lower density than NA. The bulk density of the reference samples from the natural aggregates was 2354 and 2315 kg/m³ for NAC-100-S and NAC-100-G, while the density of the concrete with a dosage of recycled aggregate was 2309 and 2251 kg/m³ for RAC-100-4/16-S and RAC-100-4/16-G. Compared to the reference concrete NAC-100-S, the concrete density decreased by 45 kg/m³ and 103 kg/m³ for RAC-100-4/16-S and RAC-100-4/16-G, respectively. Similarly, for RAC-100-4/16-S and RAC-100-4/16-G, a decrease in the density of the concrete of 6 and 64 kg/m³ was observed compared to the NAC-100-G concrete. For both concrete mixes with RA content, very small reductions in density were observed, which were likely due to the lower proportion of residual cement mortar on the RA surface.

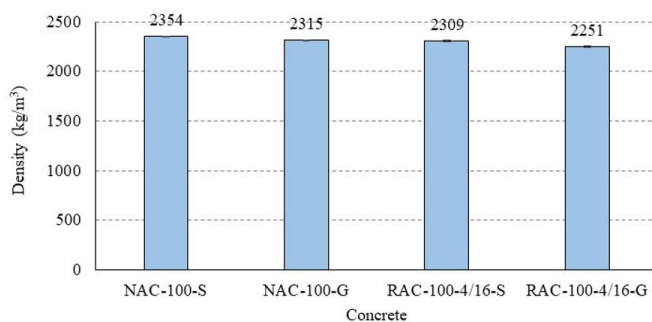


Fig. 7 Comparison of the density of the concrete

5.3 Compressive strength of the concrete cubes

Figure 8 presents the average compressive strength values of the cubes for the concrete mixture tested, while each value represents the mean value obtained from the three concrete cubes. All the specimens failed as described by the standard, which confirmed the consistency and validity of the testing process. According to various studies (Fanijo et al., 2023); (Wang et al., 2023); (Dabiri et al., 2022), the addition of recycled concrete aggregate generally results in a reduction in the compressive strength of concrete. The average compressive strength of the specimens from NA was 53.86 MPa and 56.97 MPa for the concrete NAC-100-S and NAC-100-G, respectively. For the specimens with RA content, the average values of the cube's compressive strength were 56.74 MPa and 59.74 MPa. The experimental results, therefore, show a contradictory character, as the above-mentioned research indicates a decrease in the compressive strength of the concrete, which is probably caused by the lower content of the residual adhered mortar on the surface of the recycled aggregates. The low residual mortar proportion was confirmed, despite the minimal effect of the RA on the density. On the contrary, a slight increase in the average compressive strength of the concrete was observed with the RA. For the RAC-100-4/16-S samples, it was +2.89 MPa, compared to +2.77 MPa for the RAC-100-4/16-G. The consistency of the results of the compressive strength of the concrete is also confirmed by the low values of the coefficients of variation, which were 1.43, 2.98, 7.3, and 3.46 % for NAC-100-S, NAC-100-G, RAC-100-4/16-S, and RAC-100-4/16-G. The slightly increased values of the average compressive strength of the concrete may be caused by the so-called internal treatment effect, which occurs due to the increased absorbency of RA (Khuat et al., 2024); (Adessina et al., 2023); (Wu et al., 2017).

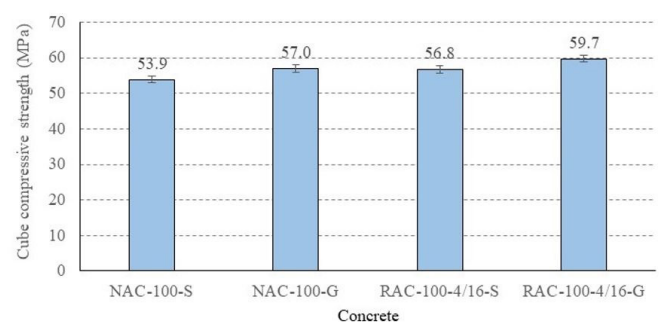


Fig. 8 Compressive strength of the concrete cubes

5.4 Results of the flexural tests

A comparison of the responses of the slabs tested at the individual loading stages (0, 5, 10, 15, 20, 22.5, and 25 kN), which were measured at quarter-span locations using digital dial gauges, is shown in Fig. 9. From the deformation curves, it can be observed that all the steel-reinforced slabs exhibited lower deformations at each loading stage than the GFRP-reinforced samples. After reaching a certain load value (above 22.5 kN), however, a more significant increase in deformations was observed, even in the samples with steel reinforcement, due to reaching the yield point in the reinforcement.

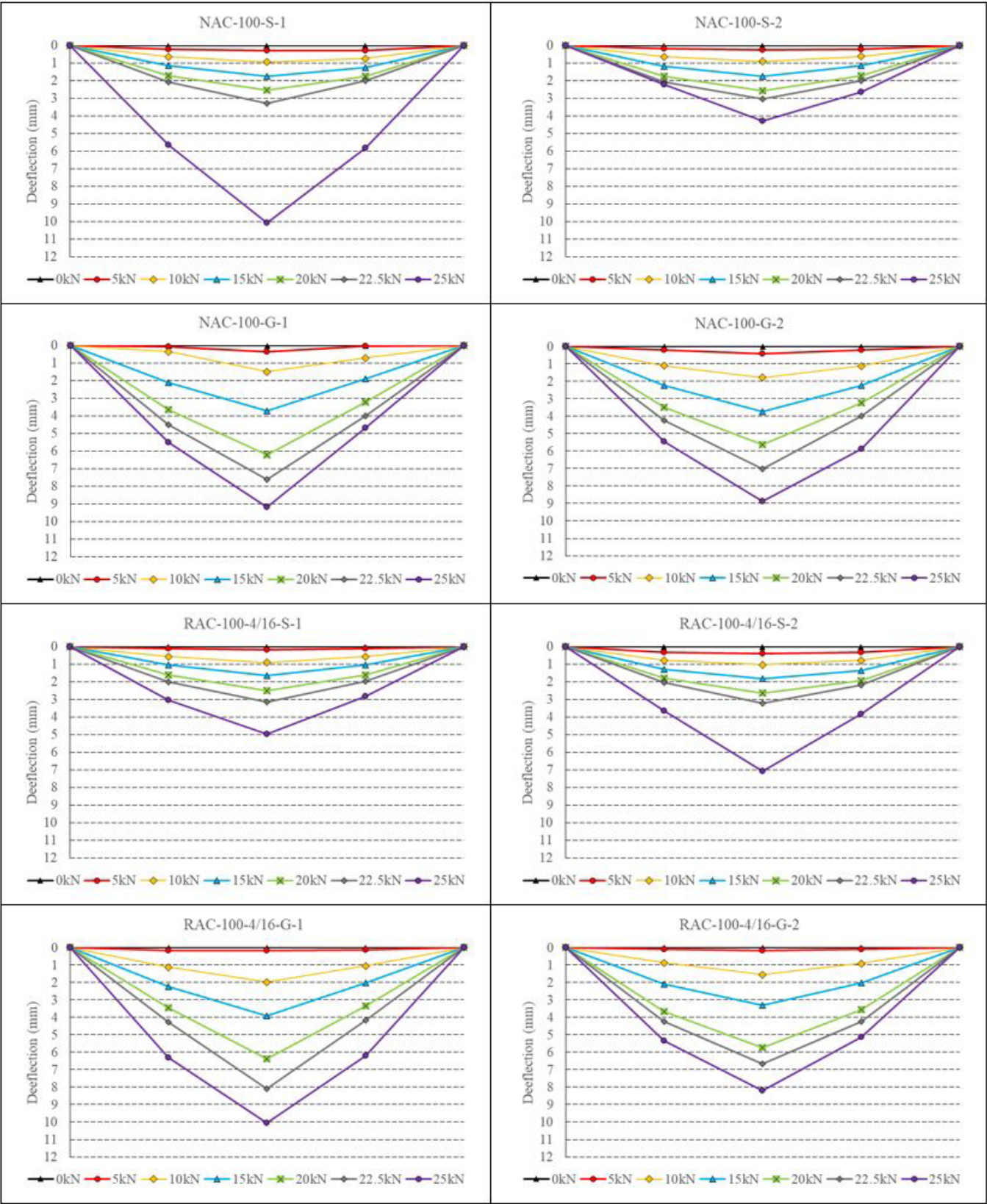


Fig. 9 Comparison of deflection of the slabs tested, depending on the load applied

The load-deflection curves for all test slabs are shown in Fig. 10. It can be observed from the deformations that the samples reinforced with GFRP showed larger deformations at the same load than those reinforced with steel rebars. Until the

first crack, which occurred at a load value of 7.15 – 9 kN for the NAC samples, or 5.06 to 7.04 kN for the RAC samples, all the slabs showed approximately the same slope. After the first crack formed, a change in the slope of the curves was observed

for the slabs reinforced with both steel and GFRP. While the change in the slope was less pronounced for the samples with steel reinforcement, the slope of the line was much more moderate for samples with a GFRP reinforcement (i.e., the deformation increased faster than for slabs with a GFRP reinforcement). Comparing the load-deflection response in Fig. 10, we can see that all the specimens failed at approximately the same load. The maximum force at the failure point was 26.28, 27.19, 26.16, and 26.05 kN for the steel-reinforced slabs

designated NAC-100-S-1, NAC-100-S-2, RAC-100-4/16-S-1, and RAC-100-4/16-S-2, respectively. Similarly, for the GFRP-reinforced specimens, the maximum force at the failure point of the member was observed to be 26.63, 26.62, 24.72, and 29.17 kN for the NAC-100-G-1, NAC-100-G-2, RAC-100-4/16-G-1, and RAC-100-4/16-G-2 slabs. The maximum load was observed for specimen RAC-100-4/16-G-2, with a value of 29.17 kN and a corresponding deformation of 10.75 mm.

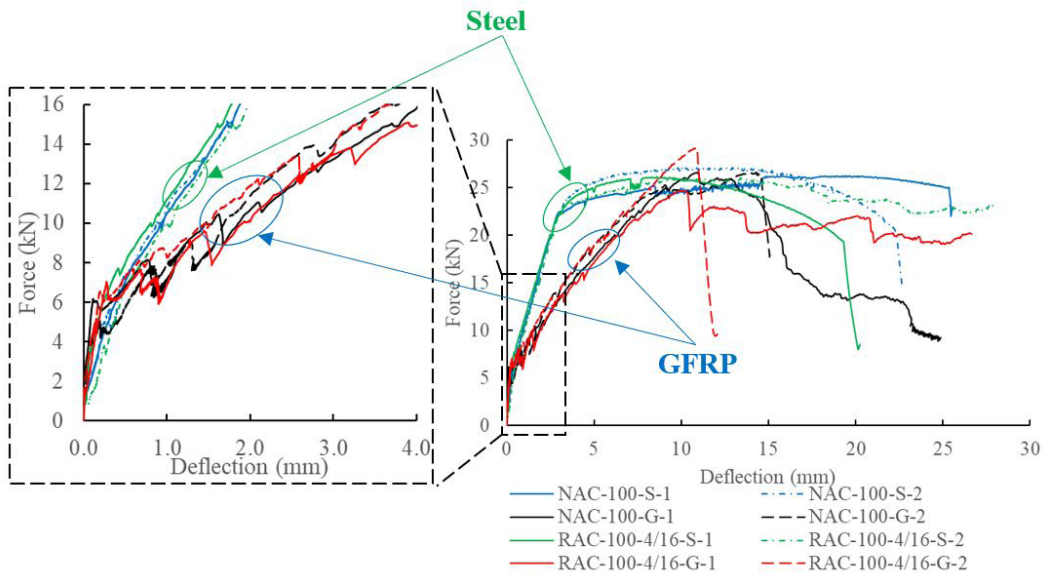


Fig. 10 Load-deflection responses of slabs

Figure 11 compares the responses of the slabs tested to an applied load of 20 kN, which corresponds to a bending moment of 4 kNm. The slabs with natural and recycled aggregates, and reinforced with steel bars, showed mid-span deflections of 2.53, 2.54, 2.49, and 2.62 mm for NAC-100-S-1, NAC-100-S-2, RAC-100-4/16-S-1, and RAC-100-4/16-S-2 at the same load level, thereby indicating comparable deformations with minimal differences between samples with the same type of reinforcement. The average slab deformation was 2.53 mm for NAC-100-S and 2.55 mm for RAC-100-4/16-S. Similarly, slabs made of both natural and recycled aggregate but reinforced with GFRP reinforcement showed mid-span deflections of 6.2, 5.628, 6.385, and 5.73 mm for NAC-100-G-1, NAC-100-G-2, RAC-100-4/16-G-1, and RAC-100-4/16-G-2 at a load of 20 kN, with an average deformation value of 5.91 and 6.05 mm for NAC-100-G and RAC-100-4/16-G, respectively. These results show that the use of concrete with recycled aggregate content did not have a significant effect on the slabs' total deformation at the load observed. In contrast, the impact of the type of reinforcement was much more significant. The average deformation for the steel-reinforced samples was 2.55 mm, whereas it was 5.99 mm for the GFRP-reinforced samples. Compared to the steel reinforcement, the deformations of slabs with GFRP reinforcement were 2.35 times larger. These results correspond to a much lower modulus of elasticity for the GFRP reinforcement, typically 45-85 GPa (Somaiah et al., 2022), compared with the steel reinforcement. In this study, helically wrapped GFRP reinforcement was used,

with an average modulus of elasticity of 54.5 GPa, which was determined from a tensile test of four GFRP bars.

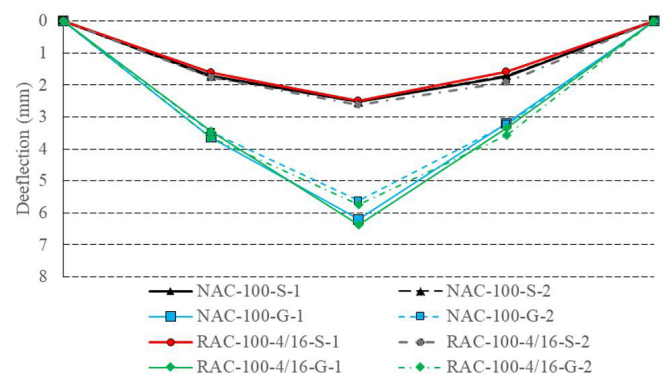


Fig. 11 Comparison of the load-deflection response of the slabs under a loading level of 20 kN

A comparison of the failure modes of the samples tested and their crack patterns is shown in Fig. 12. The figure shows that all the steel-reinforced samples failed in bending, while all the GFRP-reinforced samples failed in shear. The failure of the samples with steel reinforcement occurred due to the tearing of the concrete reinforcement or the crushing of the compressed concrete.

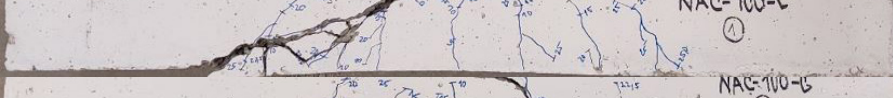
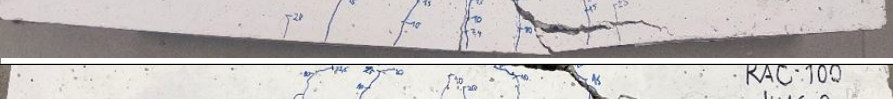
	Crack pattern	Failure mode
NAC-100-S		Bending (steel tensile rupture)
		Bending (steel tensile rupture)
NAC-100-G		Shear (concrete failure)
		Shear (concrete failure)
RAC-100-4/16-S		Bending (steel tensile rupture)
		Bending (steel tensile rupture)
RAC-100-4/16-G		Shear (concrete failure)
		Shear (concrete failure)

Fig. 12 Failure mode and cracking pattern of the tested slabs after failure

6 CONCLUSIONS

This paper presents the results of an experimental investigation of the material properties of concrete with varying RA content. Concrete members with conventional steel reinforcement, GFRP reinforcement, natural aggregate concrete (NAC), and recycled aggregate concrete (RAC) were also tested. The results depended on the type of aggregates used and the type of reinforcement. When analyzing the results, the following conclusions can be drawn:

- The dosage of recycled aggregates decreases the workability of fresh concrete. The reference concrete mixture with NAC exhibited slumps of 210 mm and 200 mm. In contrast, concrete with RA exhibited much greater reductions in workability, with slumps of 30 mm and 10 mm.
- Adding RA typically results in a decrease in the overall density of the concrete mixtures. Compared to the reference concrete, the density decreased by 4-103 kg/m³. For both concrete mixes with RA content, very small decreases in density were observed, which is likely due to the lower proportion of residual cement mortar on the RA surface.
- Adding RA did not significantly affect the decrease in the concrete’s compressive strength, which is probably due to the lower residual-adhered mortar content on the RA surface. The average compressive strength of the

specimens from NA was 53.86 and 56.97 MPa for the concrete NAC and 56.74 and 59.74 MPa for the specimens with RAC. Slightly increased values of the average compressive strength of concrete may be caused by the so-called internal treatment effect.

- From the load-deformation curve, it can be observed that all the steel-reinforced members exhibited lower deformations at each loading stage than the slabs reinforced with GFRP reinforcement.

The number of cracks was higher in the slabs reinforced with GFRP, whereas the number of cracks was lower in those reinforced with steel. Comparisons of the failure modes and crack patterns of the samples tested indicate that all the steel-reinforced samples failed in bending, whereas all the GFRP-reinforced samples failed in shear. The failure of the samples with steel reinforcement occurred due to the tensile rupture of the steel or the crushing of the concrete

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