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Flexural Behavior of GFRP-Reinforced Beams Made Of Recycled Coarse Aggregates from Waste Concrete

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Abstract - This paper reports the preliminary results from an experimental program aiming to gain a better understanding of the flexural behavior of GFRP-reinforced beams made of recycled aggregates concrete (RAC). Three 32 MPa concrete beams were designed to fail in flexure by concrete crushing before bar rupture and were tested in a four-point testing setup. The control beam was made of natural coarse aggregates (NCA). The second beam was reinforced similar to the control beam but was made of RAC. The third beam was made of RAC and contained a larger amount of longitudinal GFRP reinforcement. The behavior of the beams is reported. The compressive strength in the three beams was relatively similar. The RAC beam sustained noticeably larger deformation relative to the control beam made of NCA, but the ultimate flexural strength was relatively similar. The load-deflection response after cracking of the two RAC beams was relatively linear, which is typical behavior in GFRP-reinforced beams made using NCA. Hence, this property was not affected by the use of recycled aggregates. The calculations of the ACI 440.11 code for strength were conservative for the three beams. The calculations of this code for deflection at estimated service load level severely under-estimated the deflections.

Keywords**:** beam, deflection, flexure, GFRP bars, recycled aggregates, strength

1. Introduction

The increase in the production of concrete around the globe has increased the demand on its ingredients to unprecedented levels. Coarse aggregates are the larger contributor by volume and by weight amongst the ingredients, and the future of their supply is a concern due to the fast depletion of their natural sources.

Over the past decades, crushed waste concrete has been considered a feasible alternative source of the coarse aggregates. Its use decreases the demand on natural resources, landfills and energy [1]. However, the use of the recycled concrete aggregates (RCA) has been shown to affect the strength and durability properties of concrete, mainly due to the mortar adhered to the aggregates and to the interfacial transition zone [2, 3].

The less favorable durability properties of recycled aggregate concrete (RAC) affect its ability to protect the steel reinforcement against corrosion. One innovative solution to mitigate the threat of corrosion of the steel reinforcement is to replace the steel bars with fiber reinforced polymer (FRP) bars [4]. The most valuable advantage of FRP bars over steel reinforcement is that they do not rust. Hence, FRP bars can be used to reinforce concrete where chloride ion attacks are threats and the concrete durability properties are not very favorable, such as RAC. However, research is needed to gain a better understanding of the behavior of RAC reinforced with FRP bars.

This paper reports the preliminary results of an experimental program aimed at investigating the flexural behavior of RAC beams reinforced with glass fiber reinforced polymer (GFRP) bars. Three 32 MPa beams reinforced with GFRP bars were tested. The first beam is a control beam made with natural aggregate concrete (NAC). The second beam had similar reinforcement but was made with RAC. The third beam was made of RAC and contained a larger amount of longitudinal reinforcement relative to the two other beams. The objective of the study is to investigate the flexural behavior of RAC beams reinforced with GFRP bars.

2. Experimental Program

The beams were 200 mm in width, 420 mm in height and 2700 mm in total length. They were tested in a four-point testing setup as shown in Figure 1.

Cement conforming to ASTM C150 and tap water were used in all the concrete mixes. The fine aggregate was a sand whose water absorption and modulus of fineness were 0.96% and 2.37 respectively. The natural coarse aggregate (NCA) was Gabbro. The RCA was obtained from a plant that produces them solely from waste concrete. The water absorption was 1.04% and 6.24% and the bulk specific density was 2.71 and 2.26 for the NCA and RCA respectively. The replacement of NCA with RAC was based on volume. To achieve relatively similar compressive strength in the concrete, the water to cement ratio was 0.61 in the NAC and 0.58 in the RAC. Superplasticizers were used in all mixes.

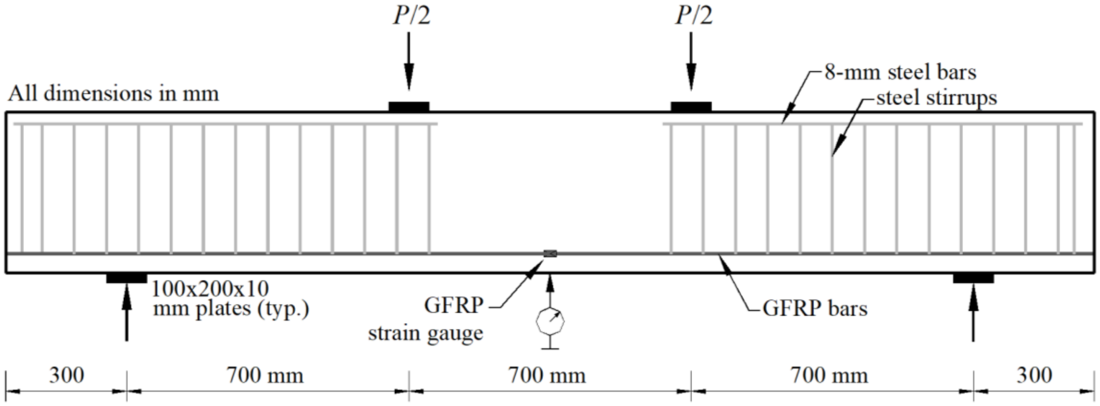

Fig. 1: Test setup and reinforcement details.

The GFRP bars were MATEEN© bars produced by Pultron. Two sizes, 16 mm and 22 mm were used. The cross-sectional area, modulus of elasticity and guaranteed ultimate strength as reported by the manufacturer for the 16 mm bars were 181.5 mm^2, 56 GPa and 850 MPa respectively. These numbers were 346.4 mm^2, 56 GPa and 836 MPa respectively for the 22 mm bars. The bars were ribbed.

Steel stirrups and top steel bars were provided in the shear spans to avoid shear failure in these regions. Two strain gauges were installed on the GFRP bars at midspan. The clear cover to the 8-mm stirrups was 20 mm. After casting, the concrete was moist-cured for seven days then was air-cured in the lab till the day of test. The deflections were measured at midspan using a dial gauge. The rate of loading was 0.1 kN/s.

Table 1: Properties of the tested beams.

Beam ID	Aggregate type	Rebars	d (mm)	A_f (mm^2)	ρ_f	f'_c (MPa)
N30–0.50	natural	$2\phi16$	364	363	0.50 %	32.8
R30–0.50	recycled	$2\phi16$	364	363	0.50 %	30.2
R30–1.44	recycled	$3\phi22$	361	1039	1.44 %	32.1

Table 1 reports the main properties of the beams. The terms d, A_f, ρ_f and f'_c refer to the effective depth of the cross section, the total area of longitudinal reinforcement, the percentage of reinforcement and the concrete compressive strength respectively. The former is based on testing standard size cylinders on the same day the corresponding beam was tested.

3. Experimental Results

Figure 2 shows the final conditions of two of the beams after failure and Figure 3 plots the load–deflection response diagrams of the three beams. Table 2 summarizes the experimental results.

3.1. General Response and Mode of Failure

The loading of the beams caused flexural cracks to appear at the bottom side within their central region. Similar cracks developed in the shear spans, which developed into shear-flexure cracks at higher loads. The beams sustained a considerable amount of vertical deflection. Beams N30-0.5 and R30-1.44 failed by concrete crushing in the pure moment region. Beam R30-0.50 failed by shear outside the test region. However, the deflections in this beam were considerably large, indicating that flexural failure was imminent had the premature failure not take place in shear. The GFRP bars were closely inspected and none of them showed any sign of rupture.

Fig. 2: Conditions of two beams after failure.

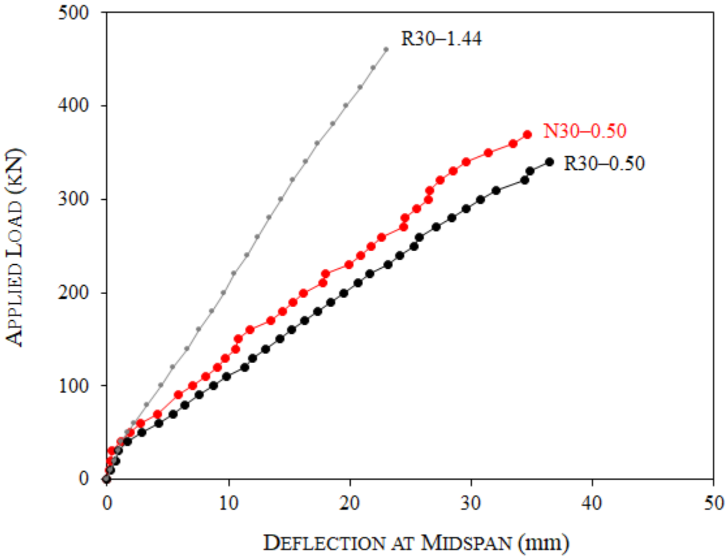

Fig. 3: Load – deflection response curves of beams.

3.3. Load-deflection response

Figure 3 shows a considerable decrease in the stiffness of the beams after cracking. It also shows that the post-response up to failure was relatively linear. This is a typical response of NAC beams reinforced with GFRP bars. Hence, use of recycled aggregates did not affect this characteristic. Figure 3 also shows that the deflections in the RAC beam noticeably higher than those in the NAC beam. The slightly lower concrete strength of the RAC beam does not account such a difference in the deflections. Hence, it can be concluded that the use of RCA increased the deflections noticeable.

Table 2: Summary of experimental results and calculations.

Beam ID	Mode of failure	P_u (kN)	$\Delta_{0.5n}$ (mm)	Δ_u (mm)	P_{n-ACI} (kN)	$\frac{P_u}{P_{n-ACI}}$	$\Delta_{0.5n-ACI}$ (mm)	$\frac{\Delta_{0.5n}}{\Delta_{0.5n-ACI}}$
N30–0.50	Flexure	370.0	10.6	34.6	278.9	1.33	8.23	1.29
R30–0.50	Shear	346.5	12.5	36.5	268.8	1.29	7.98	1.57
R30–1.44	Flexure	520.0	9.90	20.4	412.0	1.26	5.64	1.75

3.4. Ultimate strength and deformations

In Table 2, the term P_u and Δ_u refer to the ultimate measured load in the tests and the largest measure vertical deflection respectively. Service load level is assumed to be about 50% of the nominal flexural strength ac calculated using the equations of the ACI 440.1 code [4]. The term $\Delta_{0.5n}$ refers to the observed deflections at the estimated service load levels.

Table 2 and Figure 3 show that the control NAC beam resisted a slightly higher load than that resisted by its RAC counterpart. The difference was 3.6% only. The slightly lower compressive strength of the RAC beam and the fact that it failed slightly prematurely in shear indicates that the use of RCA had a limited effect on the flexural strength.

Table 2 and Figure 3 also show that the larger amount of longitudinal reinforcement in R30–1.44 relative to that in R30–0.50 lead to an increase in the flexural strength and a reduction in the deformation. The considerable effect on the strength was present in spite of the fact that the beams were over-reinforced.

4. Comparison with Calculated Properties

Table 2 lists the nominal ultimate load P_{n-ACI} calculated using the equations provided in the ACI 440.11 code for the design of GFRP-reinforced members [4]. The table also reports the ratio of the observed to the calculated ultimate load. It is shown the ratio ranged from 1.26 to 1.33. Hence, the ACI 440.11 equations provide conservative calculations of beams made of RAC of properties similar to those investigated in this study. The limited variation amongst the three ratios is favorable.

Table 2 also lists the calculated mid-span deflection $\Delta_{0.5n-ACI}$ calculated using the procedure of the ACI 440.11 code at a load corresponding to the service load level of $0.5P_n$. The table shows that the code procedure underestimated the midspan deflections. In the case of the beam with the larger reinforcement level, the deflections were severely underestimated.

5. Conclusion

Three beams reinforced in the longitudinal direction with GFRP bars were tested in flexure. One beam was a control beam and was made of natural coarse aggregates. The second beam contained similar reinforcement to the control beam but was made of recycled aggregates. The third beam was made of recycled aggregates and contained a larger amount of longitudinal reinforcement. The average compressive strength of the concrete in the beams was about 32 MPa. The following are the conclusions of the study:

1. The load-deflection diagrams of the RAC beam showed a relatively linear response after cracking. This was observed also in the NAC beam and is typical of NAC beams reinforced with GFRP bars. The linearity is mainly due to the linear stress-strain relation of the GFRP bars in tension all the way till ultimate and was not affected by the use of recycled aggregates.
2. The use of RCA as a replacement of the NCA increased the mid-span deflections noticeably of the beam. However, its effect on the flexural strength was marginal.
3. The ACI 440.11 code equations for the flexural strength were conservative in calculating the strength of the three beams. All three beams were calculated with relatively similar level of conservatism. On the other hand, the code equations for the maximum midspan deflections severely underestimated the observed results.

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