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# The effect of shear strength on load capacity of FRP strengthened beams with recycled concrete aggregate

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## HIGHLIGHTS

- FRP shear strengthening of beams with recycled concrete aggregate was investigated.
- Concrete beams with RCA have lower shear strength than beams with virgin aggregates.
- The FRP strengthening increased the load capacity of the beams more than expected.
- A novel mechanism was found that caused this unexpected result.

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## ABSTRACT

Shear failure of reinforced concrete members is brittle and catastrophic, and should be avoided. This work presents a comparative study of concrete beams with natural crushed stone and those incorporating recycled concrete aggregate (RCA). The study indicates that the equation presented in ACI 318-14 Code requirements for predicting the shear strength of concrete is less conservative for RCA concrete beams. The presented experimental investigations show that strengthening with fiber reinforced polymer (FRP) fabrics can be designed so that the shear capacity of the beams with weaker (RCA) concrete is higher than that of the control beams with natural aggregate concrete. The design of the FRP strengthening system and the reasons for the effectiveness of the design are explained.



## 1. Introduction

The use of construction and demolition waste (CDW) in concrete has been studied extensively for the past four decades [1]. CDW consisting primarily of concrete rubble can be crushed and graded into coarse aggregate referred to as recycled concrete aggregate (RCA). The use of RCAs in structural concrete is permitted by the construction codes of a number of countries, including Switzerland and Germany. These codes specify durability and strength requirements (based on standard tests), and maximum permissible amounts of non-concrete CDW materials (such as brick, wood and asphalt) as aggregates in structural concrete. Today, in several countries including Germany, Switzerland, Australia, and Spain concrete containing RCA is being marketed and used, although still in limited applications, in structural members [2]. Even though replacing natural aggregates with RCA may have little impact on reducing greenhouse gas emissions since most emissions occur due to cement production, recycling concrete decreases natural resource exploitation and reduces landfilling which both have a beneficial effect on the environment. In certain parts of the world there is a scarcity of natural aggregates close to major urban areas and the use of recycled aggregates may become more attractive and have lower overall environmental impacts when full life-cycle analysis is conducted [3]. The partial or full replacement of coarse natural aggregate (NA) with RCA is a growing trend in the concrete industry. This is mainly due to (1) increased awareness of the environmental impacts of landfilling, (2) tightening of landfilling regulations and enforcing minimum limits for the portion of CDW that must be recycled (particularly in Europe [4]), and (3) potential economic benefits due to the typically lower distances of demolition sites to recycling plants than to landfills [3].

When replacing NA with the same volume of RCA in concrete while keeping the mix volumetric proportions the same there is generally a 15–25% reduction in 28-day compressive strength [1]. This reduction can be compensated for by using more cement in the mix. However, if the load capacity of a reinforced concrete

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member does not greatly depend on the strength of concrete, such a change in mix proportioning will not be necessary. Among different possible applications of RCA in structural concrete, flexural concrete members such as beams and slabs seem to be the most viable. It is well known that the load-carrying capacity of a reinforced concrete flexural members does not have a linear relationship with the compressive strength of the concrete [5]. In fact, the concrete compressive strength mostly affects the ability of flexural member to carry load after the maximum load is reached [5]. While large ductility after failure is an important and often desired characteristic of concrete structural members, in flexural members, post-failure ductility can be achieved not only by increasing the strength of concrete, but also by optimizing the beam design through selecting lower values of the reinforcement ratio ($\rho_s$).

Flexural and shear strengthening of in-service reinforced concrete members by attaching FRP fabrics or strips is today a common practice in structural engineering [6]. Standardized design procedures, such as those provided in ACI 440.2R [7], exist for the design and construction of externally bonded FRP systems for strengthening concrete structures. FRP strengthening is a practical option when the load carrying capacity of a structure needs to be increased due to design or construction errors, damage or usage changes requiring service loads higher than what the structure was originally designed for. If, as expected, the use of RCA in flexural members become commonplace, eventually retrofitting and strengthening methods used for conventional concrete members will also be used for their RCA counterparts. A study was recently performed on the compressive strength of FRP-wrapped RCA concrete cylinders [8]. To the best knowledge of the authors no prior research has been performed on the topic of FRP strengthening of reinforced RCA concrete flexural members. A study of the previous work on RCA flexural members presented in the next section, shows that code predictions [9] can be less conservative for shear load carrying capacity than for flexural load carrying capacity of RCA concrete beams. Therefore, a strengthening system that is in particular effective in increasing the shear capacity of beams made with RCA concretes is attractive and may be found useful in the future.

## 2. Comparison of predicted vs. experimental moment and shear capacities of NA and RCA concrete beams

As mentioned earlier, codes and guidelines that currently permit the use of RCA in structural concrete define criteria and allowable limits for the composition of RCA and for a variety of physical durability and performance requirements of the RCA. However, they do not offer new design equations for determining the load-carrying capacity of structural members made with RCA concrete. Therefore, it is important to find out how well the existing methods predict the load carrying capacities of RCA structural members. This can be done, in part, by analyzing the findings of numerous prior experimental investigations reported in the literature on the behavior of reinforced concrete structural members with NA and RCA. This study uses the provisions of ACI 318 [9], which is commonly used in the United States and several other countries, to predict the beam bending moment and shear capacities.

The specific goal of the study presented in this section was to determine whether, based on the test results from prior experimental investigations reported in the literature, the load-carrying capacities of NA and RCA beams are predicted with the same margin of conservativeness according to the ACI Code. For the purpose of comparing the findings of different studies the metrics $CF_M$ and $CF_V$ are introduced for bending moment and shear load carrying capacities to normalize the results. $CF_M$ incorporates the ratio of experimental to nominal moment capacities of both NA and RCA concrete beams. If the magnitude of $CF_M$ is zero, it means that these two ratios are the same and that the code predicts the moment capacity of NA and RCA concrete beams with the same margin of conservativeness. If $CF_M$ is negative, the code is less conservative in predicting the moment capacity of RCA beams:

$$CF_M = \left(\frac{(M_{\exp,RCA}/M_{n,RCA})}{(M_{\exp,NA}/M_{n,NA})} - 1\right) \cdot 100 \tag{1}$$

A similar metric $CF_V$ is introduced for the shear load carrying capacity:

$$CF_V = \left(\frac{(V_{\exp,RCA}/V_{n,RCA})}{(V_{\exp,NA}/V_{n,NA})} - 1\right) \cdot 100 \tag{2}$$

In Eqs. (1) and (2) $M_{\exp,RCA}$ and $M_{\exp,NA}$ are the maximum experimental moment carrying capacity of RCA and NA concrete beams, respectively, which are produced and tested in the same study. $M_{n,RCA}$ and $M_{n,NA}$ are the nominal moment capacities of the RCA and NA concrete beams calculated using the provisions of ACI 318 Code, calculated from,

$$M_n = A_s f_y \left(d - \frac{a}{2}\right) \tag{3}$$

In this equation $A_s$ is the area of longitudinal tensile reinforcement section, $f_y$ is the yield strength of steel, $d$ is the effective depth and $a$ is the depth of Whitney Stress Block. Similarly, the variables in Eq. (2) are the experimental and nominal shear capacities of the RCA and NA beams and calculated from,

$$V_n = 2\sqrt{f'_c}\,bd \tag{4}$$

### 2.1. Bending moment capacity

Sato et al. [10] produced RCA concrete with 100% NA by volume replacement batches using RCAs obtained from crushing concrete specimens with different $w/c$ ratios incorporating the same type of natural aggregates used in control batches. They produced longitudinally reinforced concrete beams (with $\rho_s$ ranging from $0.13\rho_b$ to $0.56\rho_b$) and tested them in a four-point bending test configuration. Analysis of the results of 18 of their control and 100% RCA beams reveals that for beams made of concrete with $w/c = 0.6$, the average value of $CF_M$ is 2% when the NA is replaced with RCA produced by crushing concrete with $w/c = 0.6$. When both the source concrete and concrete used in the beams had the $w/c$ ratio of 0.45, $CF_M$ has an average value of 7%.

Fathifazl et al. [11,12] produced control and RCA concrete batches with 64% and 74% by weight replacement of NA with commercially produced RCA. The RCA mix proportions were designed in order that the compressive strength values of RCA concretes ($f'_{c,avg} = 40$ MPa) were slightly higher than those of their control NA counterparts. They produced several doubly-reinforced concrete beams and tested them in a 3-point bending configuration. The results from testing two control and two RCA concrete beams ($\rho_s = 0.5\rho_b$), each made from a different type of RCA or NA, show that $CF_M$ has an average value of 5%.

Bai and Sun [13] produced control and RCA concrete batches with RCA replacement of 50%, 70%, and 100% by weight. The RCA was produced in the laboratory by crushing waste test-specimen concrete ($f'_c$ in the range of 30–40 MPa). Both the NA and RCA concrete batches were proportioned to have similar compressive strength values ($f'_{c,avg} = 46$ MPa). They produced longitudinally reinforced concrete beams and tested them in four-point bending configuration to achieve flexural-tension failure. The results from testing four of their beams with the same reinforcement ratio ($\rho_s = 0.17\rho_b$) shows that $CF_M$ values were between 1.0% and 2.5% even when NA was replaced with 100% RCA.