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Experimental and Analytical Study on Recycled Aggregate RC Columns: Short and Slender Loaded Axially and Eccentrically

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Abstract: To protect the environment and preserve natural resources, it is crucial to use recycled aggregate (RA) in construction. The recycled coarse aggregate reinforced concrete columns with the addition of steel fiber evaluated under concentric and eccentric loadings for short and slender columns were examined experimentally and analytically in this research. Twenty-four column specimens were built for this study to examine the impact of steel fiber, recycled aggregate, slenderness, and eccentricity on the behavior of reinforced concrete columns. This research examined the failure mode, maximum load-carrying capacity, strain in the concrete, strain in the reinforcement, and ductility. Based on the results, it can be concluded that employing recycled concrete aggregate is a potential approach to meet design codes. The addition of 1% steel fiber effectively prevents concrete from crushing and spalling. Steel fiber, however, improved the columns' ductility and strength. The results showed the maximum load-carrying capacity of the specimens and the results of using ACI-318 code equations agreed very well. Furthermore, a model is proposed for columns with both natural and recycled aggregate and which accounts for the eccentricity and slenderness to forecast the load-carrying capacity. The outcomes demonstrated that the design principles were met well. Plots of load–moment interaction diagrams for short and slender columns made with the ACI-318 method are compared to the findings of the experiments.

Keywords: recycled aggregate concrete; steel fiber; reinforced concrete columns; eccentric compression load; concentric load

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1. Introduction

Replacing natural aggregate (NA) with recycled concrete aggregate (RA) in the concrete mix design is an important step toward a green environment [1,2]. When utilizing recycled aggregate instead of natural aggregate, the computed net carbon balance is about 20% lower [3]. The environmental and economic implications of recycled aggregates manufactured from waste concrete blocks were demonstrated to have a reduction factor of 0.420 g of CO_2/EUR cent, and this implies that using recycled aggregate will cut CO_2 emissions per unit expense [4]. Different research was conducted in past years to determine the effect of steel fiber on the behavior of structural members made with RA, and some studies have shown an improvement in the compressive strength of concrete [5,6]. Research has also shown an improvement in the shear and bending behavior [7,8]. However, it was observed that current research mainly studied the performance of columns by taking RA into account, but not with a content of steel fiber [9]. In general, the steel fibers could improve the cover–core interface and improve the strength and ductility of reinforced concrete columns [10,11]. Five series of columns were tested to determine the differences in the behavior between columns made with recycled aggregate in comparison with samples made with natural aggregate. The results showed similar behavior during the loading up to failure, as well as a similar bearing capacity and the greater ductility of the samples with recycled aggregate recorded because of the slower nature of failure [12]. The axial load of recycled aggregate concrete (RAC) columns was found to be 18% lower than that of natural aggregate concrete (NAC) columns, while the axial load improved by 2.7% when the tie spacing decreased by 22.5 percent [13]. Seventeen columns (400 × 400 × 1000) were tested with various types and qualities of recycled aggregate, along with different replacement percentages of coarse aggregate (30%, 60%, and 100%), and samples with natural aggregate. Similar cracking patterns were observed. Columns with recycled aggregate experienced a 6–8% reduction in the load-carrying capacity compared to those with natural aggregate, and the authors therefore advocated for the use of the equivalent effective water method and pre-saturated method [14]. Experimental and theoretical results reported on the use of recycled aggregates in structural applications. It was observed that, if the parent concrete had a high-strength concrete, recycled aggregate could safely replace the natural aggregate by 100% [15]. In an experimental study, thirteen short axially loaded columns were investigated to assess the influence of steel fiber and recycled coarse aggregate. The results indicated that the mechanical properties of the recycled aggregate concrete improved. Although the ductility, energy dissipation, and deformation of the columns improved with the addition of 1% steel fiber, its effect on the axial load-carrying capacity was negligible [16]. In conclusion, the replacement of natural aggregate by recycled aggregate increased the compressive, tensile, and bending strength. A negligible change was noticed in the modulus of elasticity. Controlling the fracture process observed after adding steel fiber to the mixture with recycled aggregate consequently increased the mechanical properties of the produced concrete [17]. In the conduction of an experimental test on 12 short columns loaded concentrically and eccentrically, natural aggregate was replaced by recycled aggregate with different ratios of (0, 50, 70)%. The results showed a similarity in the mechanical properties and failure modes. Some of the columns with recycled aggregate recorded a higher bearing capacity. The equivalent effective water method was used with additional water [18]. In another study, the recycled coarse aggregate was produced by crushing waste concrete cubes after being tested in the labs for compressive strength, with a w/c of 0.47–0.70 used in the mixtures. The results showed a higher compressive strength of 3–16% compared to the samples made with natural aggregate. The reported higher strength could have been due to the high water absorption by the recycled aggregate. The use of recycled aggregate was suggested in different applications [19]. It was concluded that, with the higher strength of concrete, the differences between the parent concrete and produced recycled aggregate concrete become higher. In addition, the water absorption becomes higher with the higher strength of the parent concrete [20]. It was noted that the use of recycled aggregate in construction has a major role in the future of sustainable construction and a clean environment. In the experimental research, the results showed the mechanical performance of recycled aggregate concrete is similar to that of natural aggregate concrete in an 80% replacement ratio. However, the mechanical performance of recycled aggregate concrete was not affiliated with the parent concrete [21]. In an experimental study aimed at assessing the impact of parent concrete on the mechanical properties of recycled aggregate, both high-performance recycled aggregate concrete (HPRAC) and normal-strength recycled aggregate concrete (NSRAC) were investigated. It was found that HPRAC derived from parent concrete with strengths of 80–100 MPa demonstrated mechanical properties comparable to or slightly better than those of natural aggregate concrete [22]. The recycled aggregate was produced by crushing waste concrete from pre-cast concrete columns and laboratory test cubes. Samples with 0%, 50%, and 100% replacements of recycled aggregate underwent compression strength testing, and acceptable results confirmed the feasibility of using recycled aggregate in structural applications [23]. Examining the seismic effect on 53 rectangular recycled aggregate concrete columns from different reports in the literature, the results showed that the bearing capacity of the specimens decreased and the ductility performance increased with an increase in the replacement ratio of recycled aggregate and the slenderness ratio [24].

This study's main objective is to investigate the behavior of slender, recycled coarse aggregate columns and short columns for comparison, which have not been combined in previous studies, as well as to examine the behavior of these columns at different levels of eccentricity under axial and eccentric loads. In addition, we assess if it is possible to replace all of the RA in the twenty-four reinforced concrete columns by analyzing the effects of steel fiber on the samples made of RA and NA. We also investigate the slenderness, eccentricity, ductility, strain in the concrete and steel, and axial and vertical displacement of the columns. Recently, there have been only a few studies looking into some aspects of column behavior, with one study considering slender or short columns built using recycled coarse aggregate. Therefore, many more investigation is required in the field of recycled aggregate.

2. Experimental Program

This experimental program consisted of twenty-four reinforced concrete columns. Twelve of these columns are short, with a slenderness ratio (kl/r) of 17.24, and the other twelve are slender columns with a kl/r of 34.5, where k is the effective length factor, l is the height of the column, and r is the radius of gyration. Every column made with natural coarse aggregate has an equivalent column made with recycled aggregate for comparison. Columns made with natural aggregate and recycled aggregate without steel fiber have an equivalent column made with a 1% content of steel fiber. Additionally, the columns are axially loaded in three different eccentricities, namely, e/h = 0 (concentrically loaded), e/h = 0.5 (e = 62.5 mm), and e/h = 1.0 (e = 125 mm). The specimens are identified based on how they are made. For the samples "S-RA0Vf0E0.0" and "L-RA100Vf0E0.0", S = short; L = slender; RA0 = 100% natural aggregate; RA100 = 100% recycled aggregate; V_f0 = without steel fiber; V_f1 = with a content of 1% steel fiber; E0.0 = concentrically loaded; E0.5 and E1.0 = eccentrically loaded at e/h = 0.5 and e/h = 1.0, respectively. The details of the specimens are listed in Table 1.

Table 1. Details of the tested specimens.

Specimen ID	kl/r	V_f %	e/h %	RA %
S-RA0Vf0E0.0	17.24	0	0	0
S-RA100Vf0E0.0	17.24	0	0	100
L-RA0Vf0E0.0	34.5	0	0	0
L-RA100Vf0E0.0	34.5	0	0	100
S-RA0Vf1E0.0	17.24	1	0	0
S-RA100Vf1E0.0	17.24	1	0	100
L-RA0Vf1E0.0	34.5	1	0	0
L-RA100Vf1E0.0	34.5	1	0	100
S-RA100Vf0E0.5	17.24	0	50	100
S-RA0Vf0E0.5	17.24	0	50	0
L-RA100Vf0E0.5	34.5	0	50	100
L-RA0Vf0E0.5	34.5	0	50	0
S-RA100Vf1E0.5	17.24	1	50	100
S-RA0-Vf1E0.5	17.24	1	50	0
L-RA100Vf1E0.5	34.5	1	50	100
L-RA0Vf1E0.5	34.5	1	50	0
S-RA100Vf0E1.0	17.24	0	100	100
S-RA0Vf0E1.0	17.24	0	100	0
L-RA100Vf0E1.0	34.5	0	100	100
L-RA0Vf0E1.0	34.5	0	100	0
S-RA100Vf1E1.0	17.24	1	100	100
S-RA0Vf1E1.0	17.24	1	100	0
L-RA100Vf1E1.0	34.5	1	100	100
L-RA0Vf1E1.0	34.5	1	100	0