CivilEng

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Torsional Strength of Recycled Coarse Aggregate Reinforced Concrete Beams

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Abstract: This study discusses the torsional capacity of recycled coarse aggregate (RCA) reinforced concrete beams under pure torsion based on the experimental findings available in the literature. The experimental data on RCA specimens were collected and compared with the conventional concrete specimens with key variables, such as compressive strength and longitudinal and transverse reinforcement ratios, as those variables affect the torsional capacity of reinforced concrete beams. Overall, the database consisted of experimental results from 30 RCA specimens and 256 natural coarse aggregate (NCA) specimens. The result shows that specimens with a 100 % replacement ratio have the lowest strength. In addition, as the structural mechanism of torsion is similar to the shear mechanism in reinforced concrete beams, a comparative analysis was performed with RCA specimens subjected to shear force. It was concluded that the RCA has a similar effect in strength reduction for the specimens subjected to torsion or shear with a 100% replacement ratio. However, further study and experimental evidence are required to confirm the applicability of the recycled aggregate to produce and design the structural members.

Keywords: recycled coarse aggregate; natural coarse aggregate; torsional strength; torsional cracking strength

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Citation: Ju, H.; Serik, A. Torsional Strength of Recycled Coarse Aggregate Reinforced Concrete Beams. *CivilEng* **2023**, *4*, 55–64. https://doi.org/10.3390/civileng4010004

Academic Editor: Akanshu Sharma

Received: 29 November 2022
Revised: 5 January 2023
Accepted: 6 January 2023
Published: 16 January 2023

1. Introduction

Rapid economic development and urbanization around the world has led to a huge demand for construction. In addition, many existing structures require new construction accompanied by construction and demolition waste (CDW). According to recent research findings, more than two billion tons of aggregates are produced annually in the USA, and it is predicted that this number will continue to grow [1,2]. This huge demand for aggregates raises concern about the availability of the source of natural aggregates. Furthermore, the amount of waste generated by demolition alone is estimated to be three billion tons per year in the USA, Europe, and China, with approximately 1.35 billion tones in the USA, and this waste is commonly disposed of in landfills, an emerging environmental concern [1]. Thus, the depletion of natural resources and CDW are forcing engineers to utilize construction materials in a reasonable way. Recycling the waste concrete into new construction as an alternative source of coarse aggregates can be one of the solutions to the problem.

Recycled aggregates are produced from demolition waste, and the presence of the old mortar on the surface of the recycled aggregates negatively affects their performance, making them weaker than natural aggregates. Although most studies show that recycled aggregates have lower quality, higher porosity, and lower workability compared with natural aggregates, they are still suitable for practical use. However, the study of Pani et al. [3] showed that recycled aggregate concrete has the same mechanical strength as concrete with normal aggregate. It should be carefully interpreted because the quality of the concrete with recycled aggregate would be affected by the recycling treatment method. Therefore, pre-processing is required before using the aggregates [4] to minimize the inherent adverse nature of recycled aggregates.

Comprehensive studies regarding the characteristics and material properties of recycled coarse aggregate (RCA) have been conducted in recent decades [2–7]. However, there is limited research on the structural capacity of RCA reinforced concrete members. Torsion refers to one of the structural internal forces that lead to a brittle failure of concrete structures. Therefore, it is essential to consider the torsional moment when designing concrete structures which are subjected to high eccentric loads that occur in an irregularly shaped building relevant in seismic-prone areas [8]. In this study, the experimental results on the torsional strength of recycled coarse aggregate reinforced concrete beams collected from the available literature are analyzed to discuss their torsional capacity according to the RCA replacement ratio.

Previous studies have focused primarily on the physical and mechanical properties of recycled aggregates, the methods of treatment, and the mechanism of failure. Xiao et al. [7] experimentally tested the compressive strength of RCA beams with a replacement ratio of recycled aggregate (0%, 30%, 50%, 70%, and 100%) as a key variable under uniaxial compression loading. They found that the compressive strength and modulus of elasticity of the RCA beam decreased as the RCA replacement ratio increased. For example, the elastic modulus and compressive strength of a beam with 100% recycled aggregate were significantly reduced by 45% and 11%, respectively [9].

Choi et al. [10] tested 20 beam specimens on the flexural strength of the beams with varying RCA replacement ratios (0%, 30%, 50%, and 100%) and studied the effect of the longitudinal reinforcement ratio (0.53%, 0.83%, and 1.61) and the span-to-depth ratio (1.5, 2.5, and 3.25). As a result, it was reported that the shear strength decreased as the recycled aggregate replacement ratio increased.

González-Fonteboa and Martinez-Abella [11] performed shear tests on RCA reinforced concrete beams with a 50% replacement ratio for four specimens, varying the amount of transverse reinforcement. This experimental study showed no considerable difference between RCA and NCA for the same amount of transverse reinforcement in terms of shear strength and deformation capacity. However, the early and extensive splitting cracks along the tension reinforcement were observed in specimens with recycled aggregates.

Several investigations have been conducted on the behavior of RCA reinforced concrete beams under flexure and shear, but research on the torsional strength of the RCA is very scarce. Wang et al. [12,13] have researched the seismic behavior of RCA beams under cyclic torsion by testing two types of concrete beams, one with natural aggregates and the other with 100% replacement by recycled coarse aggregates. The experimental study showed that the failure mechanism and ultimate torsional strength of both types of concrete beams were similar, however, the specimen with recycled aggregates had wider crack width and smaller cracking torsional strength [12].

Sarsam et al. [14] investigated the torsional strength of NCA and RCA beams with three different compressive strengths (25, 45, and 70 MPa) and three different replacement ratios of recycled aggregates (0%, 50%, and 100%). They reported that there is an insignificant difference in cracking and ultimate torsional strength of RCA beams with 50 % replacement compared with NCA beams, but there are considerable variations between the beams with 100% replacement.

2. Torsion Database

The main goal of this study is to examine the torsional capacity of RCA reinforced concrete beams. However, few studies have been conducted on RCA beams subjected to torsion. To this end, the experimental results from the available literature were collected and analyzed to investigate the capacity of RCA beams under pure torsion in terms of cracking and ultimate torsional strength. The data include sectional properties, such as width and height of beams, longitudinal and transverse reinforcement ratios, material properties (including the compressive strength of concrete), and the replacement ratio of

RCA. Furthermore, the cracking and ultimate torsional strength measured from tests are included. The details of the torsional database of RCA reinforced concrete beams are shown in Table 1. The test methods for torsional members are varying and can be found in the original research papers for the specimens in Table 1. Figure 1 shows sectional views of a torsional beam for the variables presented in Table 1.

Table 1. Torsional database of RCA reinforced concrete beams (A total of 37 specimens).

Ref.	Beam Name	RCA (%)	f_{ck} (MPa)	f_{yl1} (MPa)	f_{yl2} (MPa)	f_{yt} (MPa)	b (mm)	h (mm)	A_l (mm^2)	A_t (mm^2)	x_o (mm)	y_o (mm)	s (mm)	T_{cr} (kN·m)	T_u (kN·m)
Wang et al. [12]	NAC-1P	0	22.20	455.3	-	298.1	200	300	157.1	50.3	160	260	100	6.44	10.86
	NAC-1R	0	22.20	455.3	-	298.1	200	300	157.1	50.3	160	260	100	6.37	10.21
	NAC-2P	0	22.20	455.3	-	298.1	200	300	157.1	50.3	160	260	100	7.00	11.06
	NAC-2R	0	22.20	455.3	-	298.1	200	300	157.1	50.3	160	260	100	6.93	10.01
	RAC-1P	100	22.20	455.3	-	298.1	200	300	157.1	50.3	160	260	100	5.60	10.36
	RAC-1R	100	22.20	455.3	-	298.1	200	300	157.1	50.3	160	260	100	5.46	10.61
	RAC-2P	100	22.20	455.3	-	298.1	200	300	157.1	50.3	160	260	100	5.53	10.50
	RAC-2R	100	22.20	455.3	-	298.1	200	300	157.1	50.3	160	260	100	5.53	10.71
Wang et al. [13]	rAC-1-1,2P	100	28.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	7.14	14.46
	rAC-1-1,2R	100	28.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	7.38	16.20
	MRAC-1-1,2P	100	28.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	6.90	13.60
	MRAC-1–1,2R	100	28.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	6.88	13.41
	rAC-2-0,9P	100	32.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	7.29	14.86
	rAC-2-0,9R	100	32.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	7.46	16.78
	MRAC-2-0,9P	100	32.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	6.91	11.10
	MRAC-2-0,9R	100	32.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	6.50	14.02
	rAC-3-0,6P	100	32.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	6.87	14.33
	rAC-3-0,6R	100	32.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	6.58	17.09
	MRAC-3-0,6P	100	32.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	5.15	8.76
	MRAC-3-0,6R	100	32.2	467.0	550.0	420.0	200	300	804.3	50.3	160	260	100	6.40	14.00
Wang et al. [14]	RAC-1	100	25.7	298.1	-	455.3	200	300	157.1	50.3	160	260	100	5.60	8.81
	RAC-1R	100	25.7	298.1	-	455.3	200	300	157.1	50.3	160	260	100	5.46	9.02
	RAC-2	100	25.7	298.1	-	455.3	200	300	157.1	50.3	160	260	100	5.53	8.93
	RAC-2R	100	25.7	298.1	-	455.3	200	300	157.1	50.3	160	260	100	5.53	9.10
Sarsam et al. [15]	25NC	0	25.0	490.0	-	510.0	100	200	157.1	28.3	72	172	50	1.62	4.68
	45NC	0	46.0	490.0	-	510.0	100	200	157.1	28.3	72	172	50	2.16	5.22
	70NC	0	70.0	490.0	-	510.0	100	200	157.1	28.3	72	172	50	2.88	5.58
	25R50	50	24.0	490.0	-	510.0	100	200	157.1	28.3	72	172	50	1.62	4.68
	45R50	50	44.0	490.0	-	510.0	100	200	157.1	28.3	72	172	50	2.16	5.04
	70R50	50	68.0	490.0	-	510.0	100	200	157.1	28.3	72	172	50	2.88	5.40
	25R100	100	22.3	490.0	-	510.0	100	200	157.1	28.3	72	172	50	1.52	4.32
	45R100	100	42.0	490.0	-	510.0	100	200	157.1	28.3	72	172	50	1.98	4.86
	70R100	100	60.0	490.0	-	510.0	100	200	157.1	28.3	72	172	50	2.52	5.22
Li et al. [16]	RCN-1	100	25.7	550.0	-	420.0	200	300	603.2	50.3	160	260	100	5.20	12.40
	RCN-4	100	25.7	550.0	-	420.0	200	300	603.2	50.3	160	260	100	4.70	11.05
	RCN-1R	100	25.7	550.0	-	420.0	200	300	603.2	50.3	160	260	100	5.50	13.60
	RCN-4R	100	25.7	550.0	-	420.0	200	300	603.2	50.3	160	260	100	5.00	12.00

f_{ck}: compressive strength of concrete, f_{yl1}: yield stress of longitudinal reinforcement, f_{yl2}: yield stress of longitudinal reinforcement, if different diameters are used for the reinforcement, f_{yt}: yield stress of transverse reinforcement, b: width of a cross-section, h: height of a cross-section, A_l: total amount of the longitudinal reinforcement, A_t: area of a single leg of transverse reinforcement, x_o and y_o: smaller and larger center-to-center dimension of transverse reinforcement, respectively, s: spacing of transverse reinforcement, T_{cr}: cracking torsional strength, T_u: ultimate torsional strength.

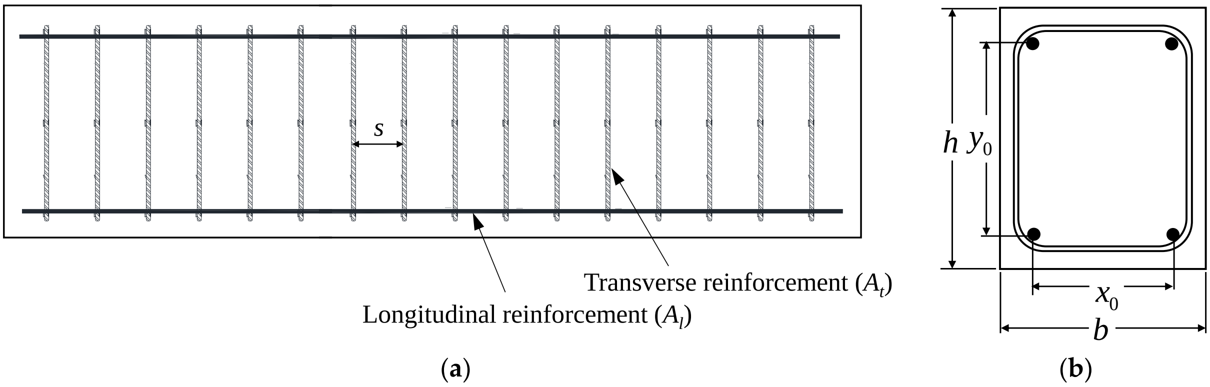


Figure 1. Cross- and longitudinal sections of specimens: (**a**) cross-section (**b**) longitudinal section.

The database consists of a total of 37 specimens, including seven NCA control specimens that were collected from five existing studies [12–16]. Significant experimental studies on the torsion of RCA reinforced concrete beams were published between 2012 and 2018. The key variable is the replacement ratio of RCA, in most cases comprised between 50% and 100%.

Figure 2 shows the distribution of key parameters of the RCA reinforced concrete specimens in the database. The compressive strength of concrete (f_{ck}) ranged from 22 to 70 MPa, as shown in Figure 2a. The longitudinal reinforcement ratio (ρ_l) ranged from 0.79% to 2.94%, while the transverse reinforcement ratios (ρ_t) are in the range of 0.7~1.38%, as presented in Figure 2b,c, respectively. For the size of the beam, 200 $\times$ 300 and 100 $\times$ 200 are considered for the width and height of beams as shown in Table 1. The reinforcement ratios in longitudinal and transverse directions (ρ_l and ρ_t) are obtained as follows:

$$\rho_l = \frac{A_l}{A_{cp}} \tag{1}$$

$$\rho_t = \frac{A_t p_h}{A_{cp} s} \tag{2}$$

where A_l is the total amount of the longitudinal reinforcement, A_{cp} is the cross-sectional area bounded by the outer perimeter of the concrete, taken as $b \times h$, and A_t is the area of a single leg of transverse reinforcement, p_h is the perimeter of the outer concrete cross-section, taken as $2(x_0 + y_0)$ where x_0 and y_0 are the smaller and larger center-to-center dimension of transverse reinforcement, respectively, and s is the spacing of transverse reinforcement.

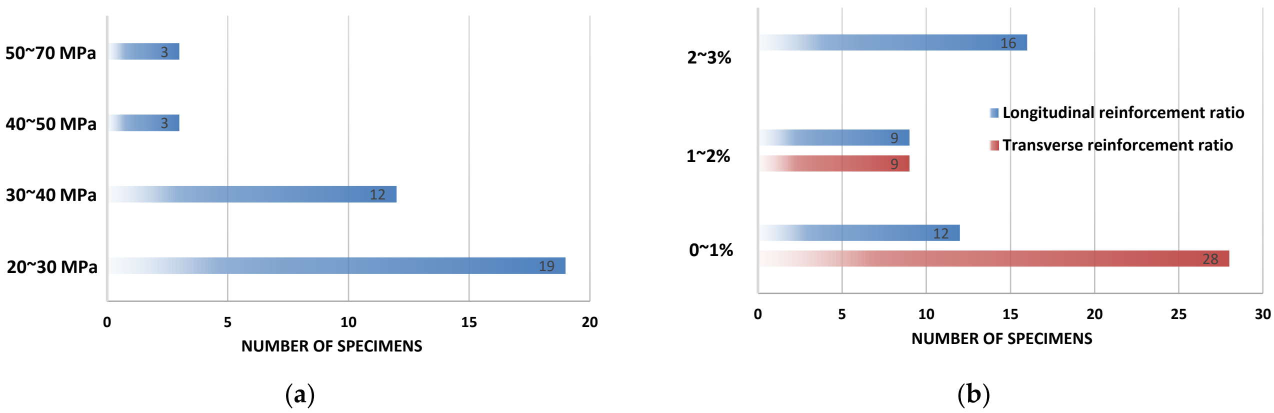


Figure 2. Distribution of key parameters in RCA: (**a**) compressive strength of concrete, MPa (**b**) longitudinal and transverse reinforcement ratios.

3. Torsional Strength of RCA Reinforced Concrete Beams

According to the literature review [2–7], recycled aggregates have an adverse effect on mechanical properties due to the attached mortar on the surface of the aggregate and it causes wider cracks. Therefore, the failure mechanism and cracking pattern of RCA specimens should be carefully compared with NCA specimens subjected to torsion. The research aims to identify how much the torsional strength of the concrete beams is affected by the replacement of recycled aggregates. Therefore, the concrete beams made of natural coarse aggregates were also used from the database reported by Ju et al. [17] The comparison was conducted on torsional strength against the RCA replacement ratio and the compressive strength of concrete to observe the difference between NCA and RCA specimens. Moreover, the evaluation of the torsional strength of the RCA reinforced concrete beams would be utilized for the feasibility of the practical application of recycled aggregate for torsional members.

Overall, 30 RCA specimens [12–16] were collected and compared with 256 conventional NCA concrete beams. To analyze the results of experiments conducted, the torsional capacity is divided into two limit states: cracking and ultimate stages. The torsional strength of the beams depends on the compressive strength of the concrete and the ratio of the transverse and longitudinal reinforcements [18–22]. Therefore, the effect of RCA replacement can be investigated by comparing the torsional capacity according to the transverse and longitudinal reinforcement ratios, and compressive strength of RCA and NCA beams.

3.1. Normalized Torsional Shear Stress

The experimental results for the torsional capacity can be normalized for reasonable and efficient interpretation of the test data [23]. The maximum shearing stresses that occurred due to torsion are calculated by the formula provided by the provisions of the ACI 318-19 [24]. The cracking torsional shear stress (τ_u) is obtained as follows:

$$\tau_u = \frac{T_u p_u}{1.7A_{oh}^2} \quad (3)$$

where T_u is the ultimate torsional strength and is the area enclosed by transverse reinforcement. In addition, the cracking torsional strength (τ_{cr}) is obtained as follows:

$$\tau = \frac{T_{cr} P_{cp}}{A_{cp}^2} \quad (4)$$

where T_{cr} is the cracking torsional strength, p_{cp} is the outer perimeter of concrete cross-section, taken as $2(b+h)$. The obtained shearing stresses were used to compare the torsional capacity of RCA and NCA beams of different sizes.

3.2. Effect of Compressive Strength

Figure 3 shows the plotted normalized torsional shear stresses versus the compressive strength of concrete for cracking and ultimate capacities. It can be observed from the figure that the cracking torsional shear stress of the RCA specimens with a replacement ratio of 100% is significantly lower than the conventional NCA concrete beams. Xiao et al. [9] investigated the effect of the RCA replacement ratio on the compressive strength of the beam and concluded that the compressive strength considerably depends on the replacement ratio of RCA. According to their study, the compressive strength of beams with 100% recycled aggregates was reduced by 11% compared with conventional concrete beams. The compressive strength of recycled aggregates depends on their properties and the amount in the concrete mix. Due to the attached mortar on aggregate surfaces, they have a higher porosity than natural aggregates. Thus, more water is required to fill the pores and obtain the same slump as natural aggregates. This influences the strength and quality of concrete which leads to a decrease in the strength of the concrete (McNeil and

Kang, 2013 [2]). Furthermore, aggregates should be washed with water under pressure to clean them from existing mortar, so the weakness induced by dirty aggregates is not relevant. As the recycled aggregates reduce the compressive strength of the beam, the cracking torsional strength which depends on the concrete strength also decreases. Thus, the figure represents that the torsional strength of RCA beams is lower than NCA beams.

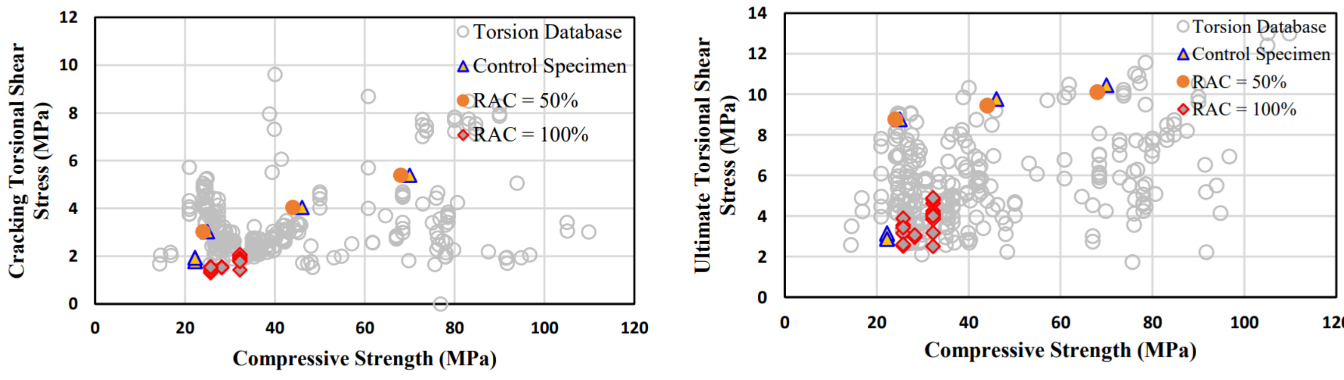


Figure 3. Effect of compressive strength: (**a**) on cracking torsional shear stress; (**b**) on ultimate torsional shear stress.

Furthermore, the cracking torsional shear stress of specimens increases as the compressive strength increases because the cracking considerably depends on the compressive strength of the specimen. Thus, the higher the strength of concrete beams, the higher the torsional resistance. A similar pattern can be seen for the specimens under the ultimate limit state. However, the ultimate capacity is not significantly affected by the compressive strength of concrete and only specimens with a 100% replacement ratio present an obvious decrease in ultimate torsional strength. In addition, although the RCA specimens are plotted on the lower boundary of the specimens in Figure 3, the torsional strength is still in line with the trend according to the compressive strength of concrete.

3.3. Effect of Reinforcement Ratios in Transverse and Longitudinal Directions

The amount of transverse and longitudinal reinforcement is one of the factors that influences the torsional capacity of the beam. Figures 4 and 5 illustrate the relationship between the torsional strength under cracking and ultimate limit states according to the reinforcement ratios in longitudinal and transverse directions, respectively. Both RCA and NCA beams showed similar capacity by increasing the longitudinal reinforcement ratio irrespective of the replacement ratio of recycled aggregates. However, when 100% of the coarse aggregates are replaced with RCA, considerable specimens showed the lowest torsional strength.

At the cracking stage, the torsional moment is resisted by the concrete strength; thus, the contribution of the longitudinal reinforcement ratio can be considered negligible. However, after cracking of the concrete, the moment is resisted by the yielding of the longitudinal reinforcement according to increasing load [6]. Therefore, at the yield and ultimate states, the torsional capacity of the beam increases with an increase in the ratio of the longitudinal reinforcement.

As for the transverse reinforcement, it is essential for providing torsional resistance after the cracking state, thus controlling the crack propagation and preventing the beam from brittle failure. As illustrated in Figure 5, the torsional capacity increases as the amount of transverse reinforcement increases. However, the influence of the transverse reinforcement ratio on cracking torsional strength is negligible because cracking is mainly controlled by concrete strength. Due to the limited test data, the specimens with a 50% of RCA replacement ratio were within the range of control specimens according to the transverse reinforcement ratio.

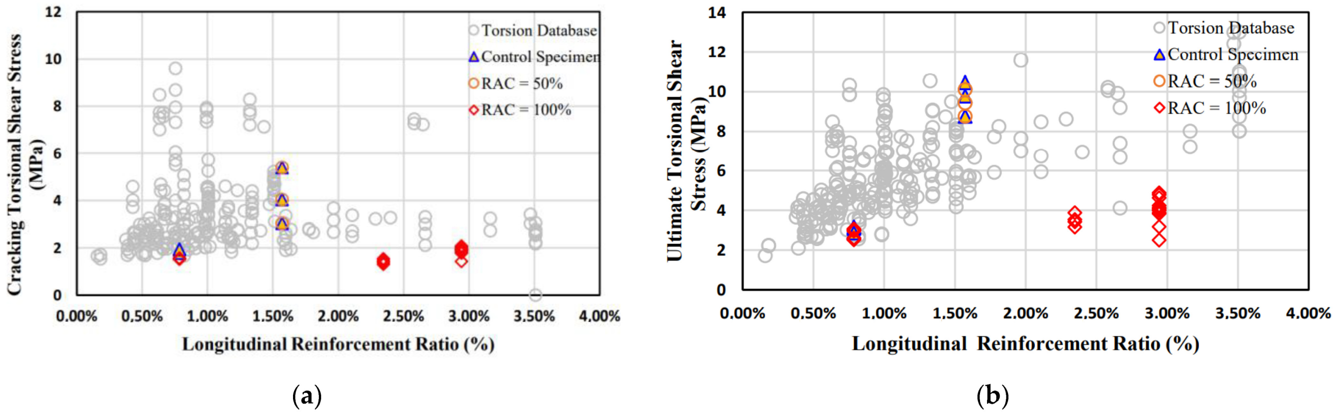


Figure 4. Effect of longitudinal reinforcement: (**a**) on cracking torsional shear stress; (**b**) on ultimate torsional shear stress.

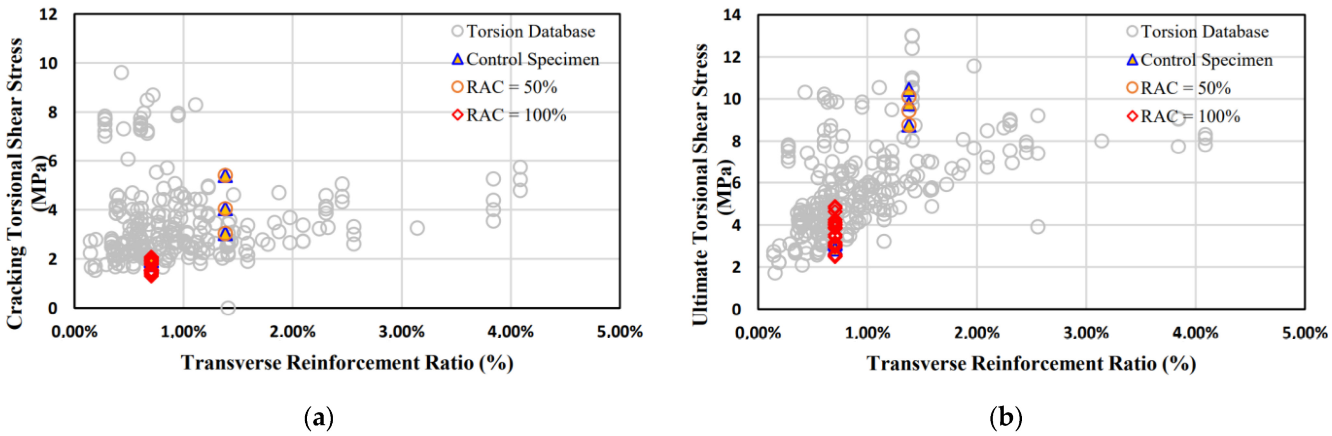
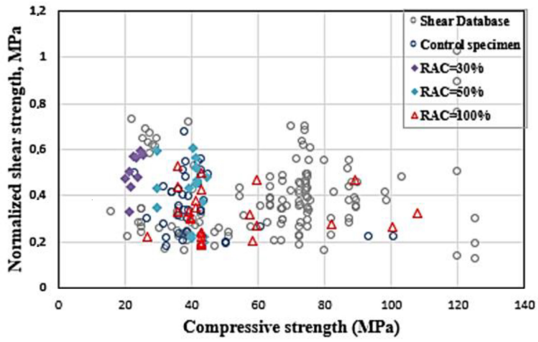


Figure 5. Effect of transverse reinforcement: (**a**) on cracking torsional shear stress; (**b**) on ultimate torsional shear stress.

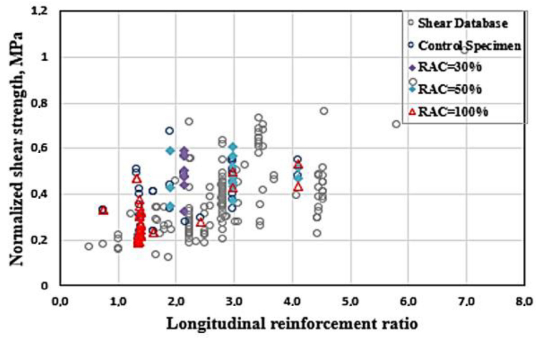
3.4. Comparison with Shear Strength

The torsional moment that acts on a beam cross-section induces shearing stress. Thus, the design of the torsion is generally related to the design of the shear [18]. For this reason, the torsional capacities of RCA and NCA beams are compared with the shear capacity. Overall, about 122 specimens with varying RCA replacement ratios from 0 to 100 % were collected from the previous study [25] and compared with the NCA specimens according to compressive strength and reinforcement amount.

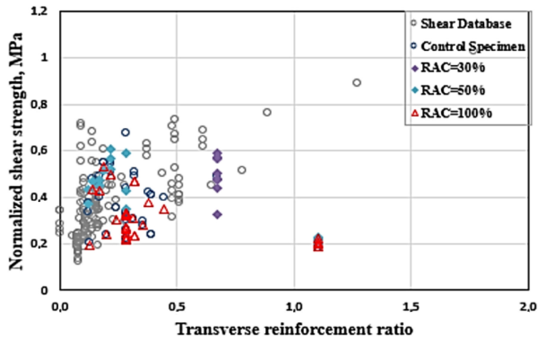
Figure 6 presents the normalized shear strength of shear specimens according to the key variables. Similar to torsional strength, when the coarse aggregates of specimens were replaced by 100 % recycled aggregates, the shear strength appeared the lowest. However, specimens with a 50% or less replacement ratio showed a shear behavior similar to conventional concrete beams.



(**a**)



(**b**)



(**c**)

Figure 6. Shear test results of RCA and NCA reinforced concrete beams: (**a**) effect of compressive strength; (**b**) effect of longitudinal reinforcement; (**c**) effect of transverse reinforcement.

4. Conclusions

This study investigated the influence of recycled aggregate on the torsional capacity of reinforced concrete beams. The comparison was made on the experimental database collected from the literature and it showed that specimens with a 100% replacement ratio have lower torsional strength than the conventional concrete beams. Since the strength characteristics of the concrete have more influence on cracking, the recycled aggregates have more influence on the cracking strength of the concrete. Thus, the cracking torsional strength is lower for specimens with natural aggregates that have been completely replaced with recycled aggregates. Overall, although RCA has a lower quality and negative effect on concrete strength, it is still not confirmed that RCA is insufficient for structural members. The torsional capacity of RCA concrete beams with a lower replacement ratio is unclear due to the lack of experimental data available. Thus, more large-scale experimental studies are required to reach a definite conclusion regarding the torsional capacity of reinforced concrete beams using recycled aggregates.

Experiments should be conducted with different replacement ratios because a lower replacement ratio may result in torsional behavior similar to NCA beams. Previous studies on flexural and shear performances of RCA beams conclude that the beams with a replacement ratio of 50 % or less show the same behavior as the NCA specimens. As the torsion and shear have similar structural behaviors, it can be expected that the torsional strength of beams with 50% or less RCA would have a capacity similar to the conventional concrete specimens. To conduct a more comprehensive study regarding the effect of the reinforcement ratio, the reinforcement ratios in longitudinal and transverse directions should be also conducted in the experimental study. As the principal reason for the weak structural performance of the recycled aggregates is their quality and strength, treatment methods to improve their efficiency and workability should be evaluated and studied.

Author Contributions: Conceptualization, methodology, writing—review and editing, supervision, funding acquisition, H.J.; validation, investigation, data curation, writing—original draft preparation, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) funded by the Korean Government (MSIT) [(No. 2021R1C1C2093437)].

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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