Effect of Recycled Coarse Aggregate Quality on Compressive Strength of Concrete at Different Replacement Levels

Arusmalem Ginting[1*], One Selfiana Fitri Winarno[1], and Prasetya Adi[1]

[1] Department of Civil Engineering, Janabadra University, Yogyakarta, Indonesia

* Correspondence: aginting@janabadra.ac.id

Abstract: Recycled Coarse Aggregate (RCA) is produced from the processing of construction and demolition waste and is used as a replacement for Natural Coarse Aggregate (NCA). Waste concrete cylinders from compressive-strength testing in precast concrete factories are readily available but have not been optimally utilized. One potential solution for utilizing this waste is to recycle it into RCA. In previous studies, the quality of the RCA used was generally not known with certainty; therefore, its effect on Recycled Aggregate Concrete (RAC) remains to be further investigated. This study aims to determine the effect of RCA quality on the compressive strength of new concrete. The RCA used in this research consists of six quality levels: RCA67 (f'c = 67 MPa), RCA58 (f'c = 58 MPa), RCA50 (f'c = 50 MPa), RCA30 (f'c = 30 MPa), RCA25 (f'c = 25 MPa), and RCA20 (f'c = 20 MPa). NCA was replaced with RCA at two replacement levels: 50% and 100%. The tests included aggregate properties, slump, compressive strength, and unit weight. The results showed that the compressive strength of Natural Aggregate Concrete (NAC) with 100% NCA was higher than that of RAC with either 50% or 100% RCA. Compared to NAC, the compressive strength of RAC decreased by 14.11%–43.58% with 100% RCA and by 1.53%–13.75% with 50% RCA. The compressive strength of RAC decreased as the quality of RCA decreased. RCA quality had a significant effect on concrete compressive strength at both replacement levels.

Keywords: Recycled coarse aggregate; natural coarse aggregate; natural aggregate concrete; recycled aggregate concrete; compressive strength

1. Introduction

Recycled Coarse Aggregates (RCA) are produced by processing construction and demolition waste, primarily from old concrete structures, to serve as a replacement for Natural Coarse Aggregates (NCA) in new concrete mixes. Their use supports environmental sustainability by reducing landfill waste and conserving natural resources [1,2]. Waste concrete specimens from laboratory testing can be crushed and recycled for use as coarse aggregates in new concrete [3,4]. RCA, obtained from construction and demolition waste, has a specific gravity of 2.21-2.66, a density of 1270-1487 kg/m³, and an abrasion value of approximately 37%. Generally, the compressive, tensile, and flexural strengths of Recycled Aggregate Concrete (RAC) are about 10%–20% lower compared to those of Natural Aggregate Concrete (NAC) [5]. The water absorption of RAC increases with increasing NCA replacement by RCA [6–8]. The manufacturing process of RCA generally involves the following main

steps: collection of construction and demolition waste, crushing, cleaning and sorting, grading, and quality control [9]. RCA can be used as a partial or full replacement for NCA in concrete mixes, with performance impacts varying with the replacement level and application [10].

Tran et al. [11] conducted a study on RAC with NCA replaced by RCA at levels of 25%, 50%, 75%, and 100%. The workability of RAC decreased with increasing RCA content. The compressive strength of RAC was 5.0–9.3% lower than that of NAC, primarily due to a weaker interfacial transition zone (ITZ). The elastic modulus of RAC was also lower than that of NAC, with a difference of 7.7% at 100% RCA content. Qasim et al. [12] used RCA from construction waste to replace NCA at levels of 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. The workability of RAC decreased with increasing NCA replacement, due to the RCA's rough surface texture. The compressive strength also decreased as the NCA replacement level increased. Al-Shamaa et al. [13] used building rubble as RCA to replace NCA at 0%, 35%, 65%, and 100% levels. Replacing NCA with 100% RCA resulted in lower slump values. NAC had an average density of 2390 kg/m³, while RAC, with 100% RCA, had a significantly lower density of 2116 kg/m³ (11% lower). Compared to NAC, RAC with 100% RCA showed a 64% decrease in compressive strength, a 71% decrease in tensile strength, a 62% decrease in flexural strength, and a 12% decrease in density. Buller et al. [14] used demolished concrete as RCA to replace 50% of the NCA in concrete mixes. The RCA had a water absorption of 3.90%, which was 120% higher than that of NCA. Its specific gravity was 2.40, approximately 5% lower than that of NCA. The density of RAC was 1960 kg/m³, 11% lower than that of NAC. The compressive strength of RAC was 6.95% lower than that of NAC. Halahla et al. [15] used demolished concrete waste as Recycled Coarse Aggregate (RCA) for 100% replacement of NCA. The RCA had significantly higher water absorption, almost twice that of NCA, which must be considered in concrete mix design. The compressive strength of RAC was approximately 10% lower than that of NAC, while its splitting tensile strength was about 4% lower. Hassan [16] used RCA to replace NCA at levels of 20%, 40%, 60%, 80%, and 100%. Increasing the RCA percentage decreased the slump. However, replacing NCA with RCA at these levels had little effect on the concrete's compressive strength.

Demolished column waste was used as RCA to replace NCA at levels of 10%, 20%, 30%, 40%, 50%, and 100%. The compressive, flexural, and splitting tensile strengths of the concrete were reduced as the proportion of demolished column waste in the mixture increased [17]. Concrete pile waste was used as RCA to replace 100% of the NCA. The resulting RAC exhibited greater compressive strength than the NAC [18]. The company's recycled coarse aggregate was used as RCA to replace NCA at 0%, 30%, 40%, and 50%. The slump values achieved met the target requirements. Replacement of NCA with RCA was feasible up to 50%, with the compressive strength of RAC being equal to or exceeding that of NAC [19]. Crushed tested cylinders were used as RCA to replace NCA at levels of 0%, 20%, 40%, 60%, 80%, and 100%. Substituting NCA with varying proportions of RCA had no adverse effect on the consistency of the concrete mixture. In the case of Normal Strength Concrete (NSC), the incorporation of RCA led to an average decrease of 9.8% in compressive strength, 13.5% in splitting tensile strength, and 11% in elastic modulus. For High Strength Concrete (HSC), the reductions averaged 11% for compressive strength, 10.3% for splitting tensile strength, 10.8% for flexural strength, and 11.3% for elastic modulus [20].

In precast concrete factories, concrete cylinder waste from compressive-strength testing is abundant but is not optimally utilized. One potential solution to maximize the benefits of this waste is to recycle it for use as a replacement for NCA in new concrete mixes. Utilizing concrete cylinder waste in this manner can reduce the demand for NCA and minimize waste accumulation. In previous studies, the quality of RCA used as an NCA replacement was often unknown, necessitating investigation of its effect on the properties of new concrete. In precast concrete factories, concrete cylinder waste can be classified by original concrete strength. This study aims to evaluate the correlation of RCA quality, as a replacement for NCA, to the compressive strength of RAC. This study hypothesizes that RCA quality influences the compressive strength of RAC.

2. Materials and Methods

2.1 Concrete components

2.1.1 Cement

This study utilized Type I Ordinary Portland Cement (OPC), which has a specific gravity of 3.15, a fineness of 160 m²/kg, a minimum initial setting time of 60 minutes, and a maximum final setting time of 600 minutes.

2.1.2 Sand

The sand used in this study was sourced from Srumbung, Magelang, Indonesia. The tests performed included silt content analysis [21], specific gravity and absorption [22], unit weight [23], water content [24], fineness modulus, and gradation [25]. The results of the sand tests are presented in Table 1. The sand is classified as rather coarse, falling within Zone II, as shown in Figure 1.

Table 1. Test results of sand.

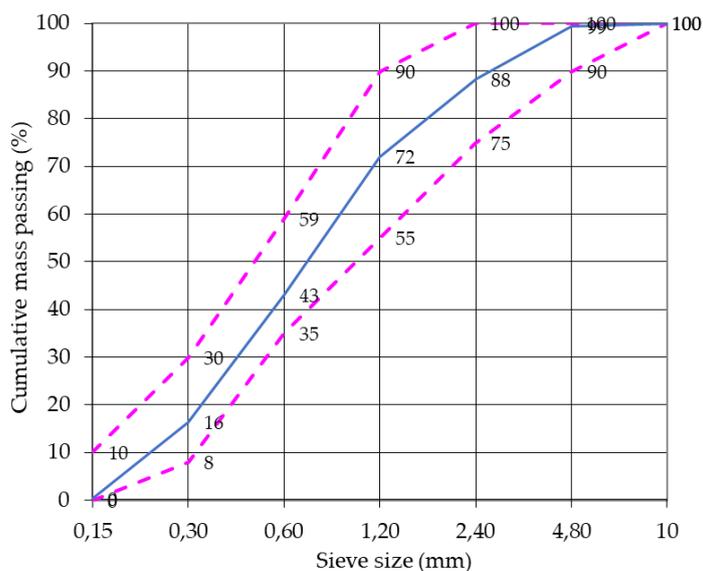| Types of testing	Results	Unit
Silt content	2.300	%
Specific gravity	2.558	-
Absorption	2.776	%
Unit weight	1.379	g/cm³
Water content	4.146	%
Fineness modulus	2.806	-

Figure 1. Gradation of sand.

2.1.3 Natural Coarse Aggregate (NCA)

In this study, the NCA was produced from crushed stone supplied by a quarry in Clereng, Kulon Progo, Yogyakarta, Indonesia. The tests performed included silt content analysis [21], specific gravity and absorption [26], unit weight [23], water content [24], fineness modulus, abrasion value, and gradation [25]. The results of the NCA tests are presented in Table 2. The maximum particle size of the NCA is 20 mm, as shown in Figure 2.

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Table 2. Test results of NCA.

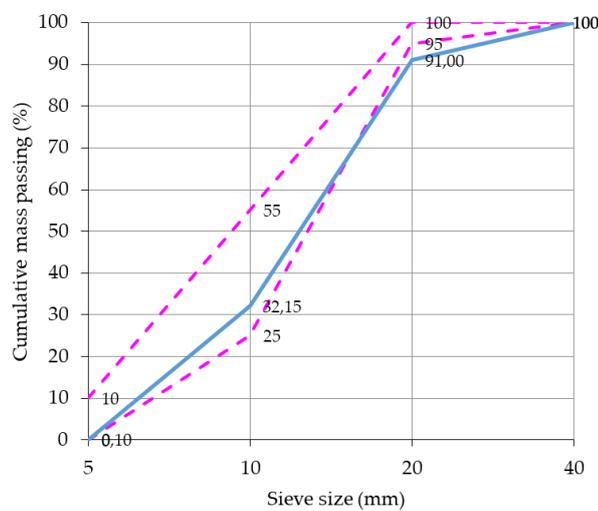| Types of testing	Results	Unit
Silt content	0.550	%
Specific gravity	2.635	-
Absorption	2.145	%
Unit weight	1.319	g/cm³
Water content	1.199	%
Fineness modulus	6.766	-
Abrasion value	22.880	%

Figure 2. Gradation of NCA.

2.1.4 Recycled Coarse Aggregates (RCA)

The RCA used in this study was derived from concrete cylinder waste obtained from compressive strength testing, as shown in Figure 3. The waste cylinders were crushed at a stone-crushing plant and then sieved. The RCA was classified into six categories based on different mix designs: 67 MPa (RCA67), 58 MPa (RCA58), 50 MPa (RCA50), 30 MPa (RCA30), 25 MPa (RCA25), and 20 MPa (RCA20). The results of the RCA tests are presented in Table 3. The maximum particle size of the RCA is 20 mm, as shown in Figure 4.

Figure 3. Concrete cylinder waste: A) Before crushing, B) After crushing.

Table 3. Test results of RCA.

| Types of testing	RCA67	RCA58	RCA50	RCA30	RCA25	RCA20	Unit
Silt content	0.60	1.00	0.95	2.65	2.10	2.80	%
Specific gravity	2.577	2.506	2.469	2.439	2.387	2.457	-
Absorption	2.723	3.735	3.040	4.604	4.064	4.336	%
Unit weight	1.331	1.280	1.297	1.268	1.267	1.267	g/cm^3
Water content	0.452	0.503	0.898	1.200	0.503	0.751	%
Fineness modulus	6.686	6.730	6.654	6.521	6.476	6.546	-
Abrasion value	26.900	27.220	27.180	36.960	40.240	39.660	%
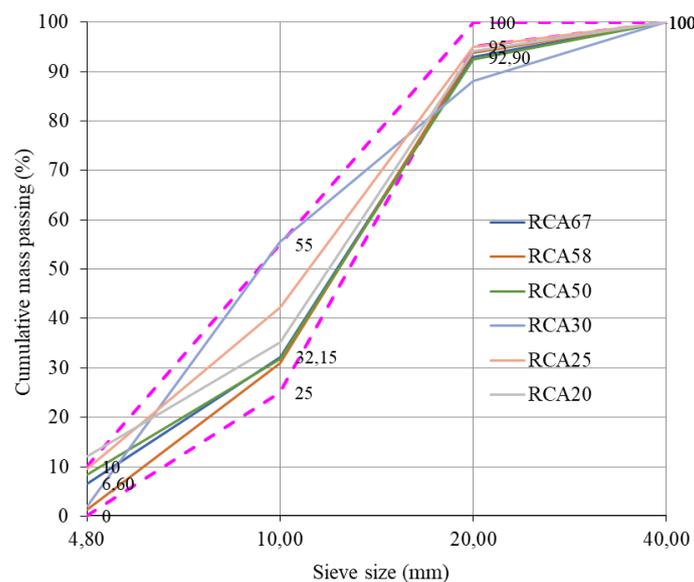
Figure 4. Gradation of RCA.

2.2 Mix design

The mix design was prepared in accordance with the Indonesian National Standard SNI 03-2834-2000. [25] The mix design followed the methods for normal concrete mix design as specified in the Indonesian National Standard SNI 03-2834-2000, for 1 m³ of concrete with a target compressive strength of 25 MPa at 28 days, the mix proportions were as follows: 205 liters of water, 477 kg of cement, 652 kg of fine aggregate, 1019 kg of coarse aggregate, and a water–cement ratio of 0.43. The target slump value was 60–180 mm. The water and aggregate requirements in the mix design were based on saturated surface-dry (SSD) conditions. The aggregates used were air-dry condition, so the water volume and weight of the aggregates were adjusted based on the absorption value and actual water content of the aggregates. The test specimens were concrete cylinders with a diameter of 150 mm and a height of 300 mm. NCA was replaced with RCA at 50% and 100% replacement levels, with the specimen variations presented in Table 4.

Table 4. Test specimens.

Mix Code	f'c of RCA (MPa)	NCA (%)	RCA (%)	Number of test specimens	Material requirements for 1 m³ of concrete				
					Cement (kg)	Sand (kg)	NCA (kg)	RCA (kg)	Water (L)
100NCA	-	100	0	3	477	660	1009	0	206
100RCA67	67	0	100	3	477	651	0	981	219
100RCA58	58	0	100	3	477	640	0	955	228
100RCA50	50	0	100	3	477	633	0	956	217
100RCA30	30	0	100	3	477	628	0	937	229
100RCA25	25	0	100	3	477	621	0	923	231
100RCA20	20	0	100	3	477	632	0	940	231
50RCA67	67	50	50	3	477	655	501	494	212
50RCA58	58	50	50	3	477	650	497	485	217
50RCA50	50	50	50	3	477	647	494	488	212
50RCA30	30	50	50	3	477	644	492	480	218
50RCA25	25	50	50	3	477	640	489	476	219
50RCA20	20	50	50	3	477	646	494	480	219

2.3 Concrete cylinder testing

Compressive strength testing of the concrete cylinders was conducted after 28 days of curing, in accordance with the Indonesian National Standard SNI 1974-2011 [27]. The curing method used was water curing at 23 ± 1.7 °C. The compressive strength testing machine used had a capacity of 2000 kN, with a loading rate of 0.15-0.35 MPa/s.

3. Results and Discussion
3.1 Coarse aggregate test results
3.1.1 Silt content

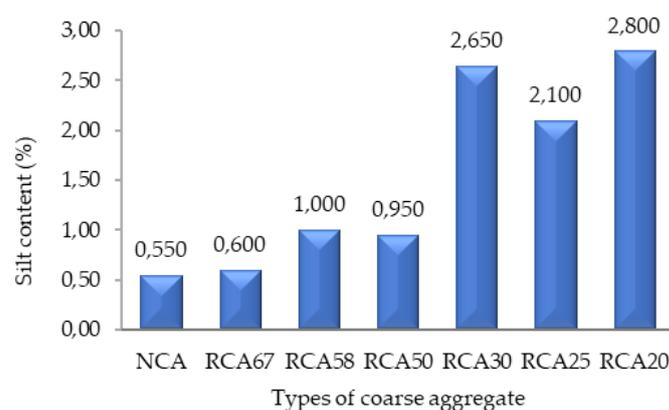The results of the silt content test are shown in Figure 5.

Figure 5. Silt content.

Figure 5 shows that the silt content, defined as the proportion of material passing the No. 200 sieve (0.075 mm), is lower for NCA compared to RCA. A decreasing RCA quality or original compressive strength corresponds to an increase in silt content. This is attributed to the higher amount of residual mortar or adhered old concrete, which tends to disintegrate during the recycling process. Based on the analysis of variance (ANOVA), the obtained F-value was 9.1429 with degrees of freedom (5,6) and a p-value of 0.0089, indicating that the quality of RCA significantly affects silt content.

3.1.2 Specific gravity

The results of the specific gravity test are presented in Figure 6. The specific gravity of NCA is higher than that of RCA. Furthermore, a decrease in RCA quality or compressive strength corresponds to a reduction in its specific gravity.
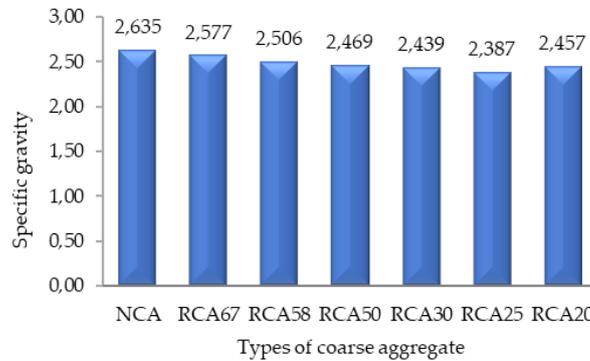

Figure 6. Specific gravity.

Based on the results of the analysis of variance (ANOVA), the obtained F-value was 16.0764 with degrees of freedom (5,6) and a p-value of 0.002, indicating that the quality of RCA has a significant effect on specific gravity.

3.1.3 Absorption

Figure 7 presents the results of the absorption test, showing that NCA exhibits lower water absorption compared to RCA. This higher absorption in RCA is primarily due to residual mortar or old adhered concrete on its surface, which increases its water-uptake capacity.
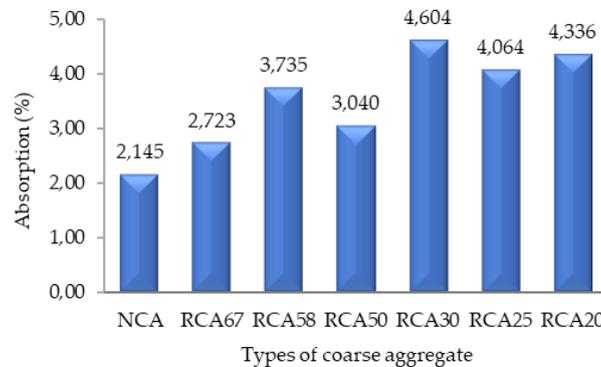

Figure 7. Absorption.

Based on the analysis of variance (ANOVA), the obtained F-value was 2.0248 with degrees of freedom (5,6) and a p-value of 0.2077, indicating that the quality of RCA does not have a significant effect on absorption.

3.1.4 Unit weight

The results of the unit weight test are presented in Figure 8. Overall, the unit weight of NCA is higher than that of RCA.

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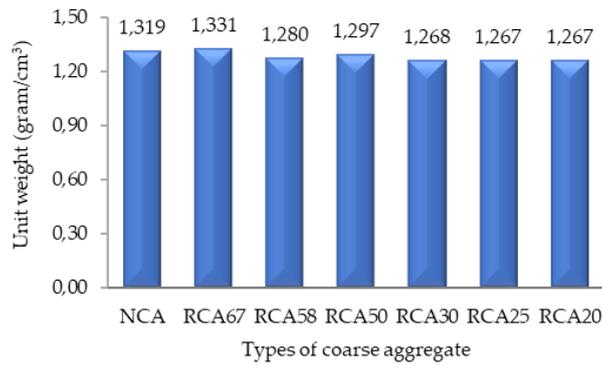
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Figure 8. Unit weight.

Based on the results of the analysis of variance (ANOVA), the obtained F-value was 1.7014 with degrees of freedom (5,6) and a p-value of 0.2673, indicating that the quality of RCA does not have a significant effect on unit weight.

3.1.5 Fineness modulus

The results of the fineness modulus test are presented in Figure 9. The fineness modulus of NCA is nearly the same as that of RCA, indicating that the coarseness of both aggregates used in this study is comparable.
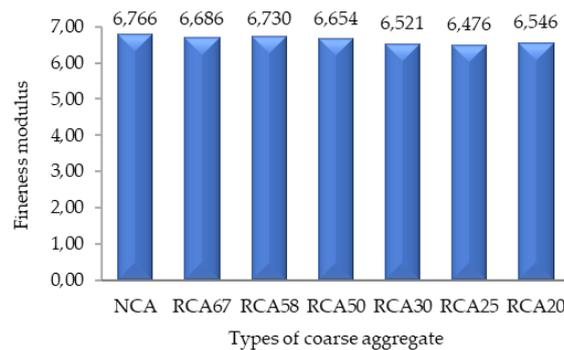

Figure 9. Fineness modulus.

3.1.6 Abrasion value

Figure 10 illustrates the results of the abrasion test, showing that the abrasion value of NCA is lower than that of RCA, indicating that NCA has greater resistance to wear. Additionally, the data indicate that a reduction in RCA quality or compressive strength is associated with an increase in its abrasion value.
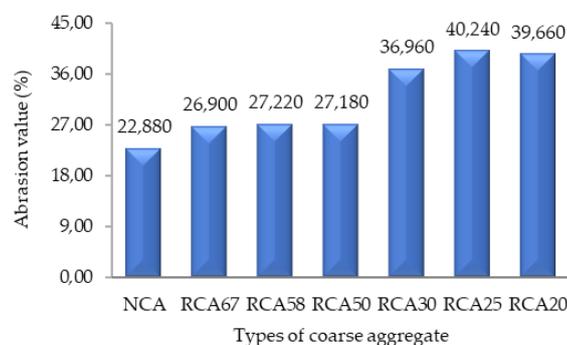

Figure 10. Abrasion value.

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3.2. Slump value

The results of the slump value test are presented in Figure 11. The figure illustrates the slump values of mixtures containing NCA, RCA, and a combination of NCA and RCA. All mixtures achieved slump values within the target range of 60–180 mm. Although RCA exhibits higher water absorption than NCA, this does not significantly affect the slump value, provided that water content adjustments are made to the mixture in accordance with the aggregate's absorption capacity and moisture condition.
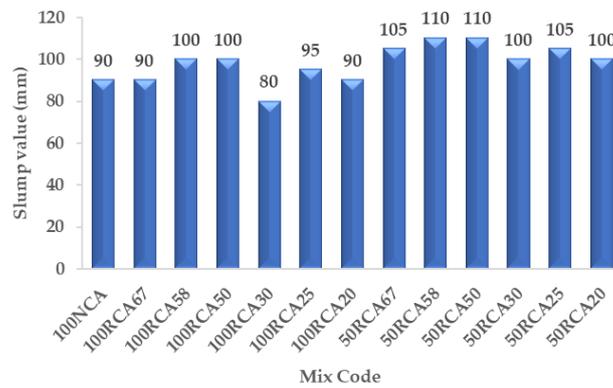

Figure 11. Slump value.

3.3 Compressive strength

The compressive strength test outcomes are displayed in Table 5, Figure 12, and Figure 13. As indicated in Table 5 and Figure 12, the compressive strength of NAC made with 100% NCA is greater than that of RAC composed entirely of RCA. Furthermore, the compressive strength of RAC declines as RCA quality decreases. The mix incorporating 100% RCA with a compressive strength rating of 67 MPa (100RCA67) attained 85.89% of the strength achieved by the 100% NCA mix (100NCA), surpassing the findings reported by Noshin et al. [28] at 84.21%, and Hassan et al. [29] at 73.65%. The compressive strength of concrete containing 100% RCA with compressive strength classes of 58 MPa, 50 MPa, 30 MPa, 25 MPa, and 20 MPa reached 72.87%, 66.28%, 58.38%, 54.17%, and 56.42%, respectively, of the compressive strength of concrete containing 100% NCA. These values are lower than those reported by Noshin et al. [28] (84.21%) and Hassan et al. [29] (73.65%).

Table 5. Compressive strength.

| Mix Code	f'c of RCA (MPa)	NCA (%)	RCA (%)	Average compressive strength		Std. Dev.	F-value	P-Value
				MPa	%			
100NCA	-	100	0	33.38	100	2.6695		
100RCA67	67	0	100	28.68	85.89	4.6879		
100RCA58	58	0	100	24.33	72.87	1.3400		
100RCA50	50	0	100	22.13	66.28	1.1002		
100RCA30	30	0	100	19.49	58.38	1.1505	10.541	0.00046
100RCA25	25	0	100	18.08	54.17	1.2053		
100RCA20	20	0	100	18.84	56.42	0.3592		
50RCA67	67	50	50	32.87	98.47	1.2354		
50RCA58	58	50	50	32.18	96.41	2.2266		
50RCA50	50	50	50	32.64	97.78	0.2650		
50RCA30	30	50	50	31.19	93.42	1.0725	4.25	0.01863
50RCA25	25	50	50	28.79	86.25	0.8657		
50RCA20	20	50	50	30.10	90.16	1.5516		
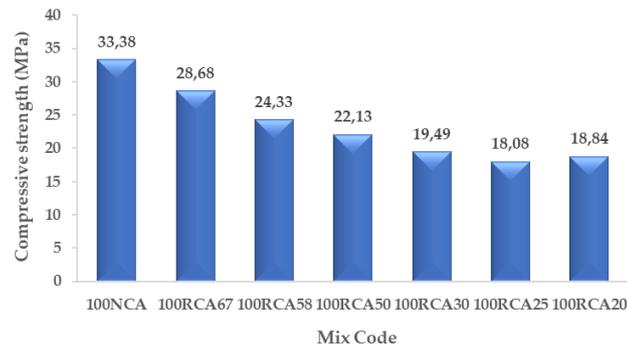
Figure 12. Compressive strength of concrete with 100% RCA.
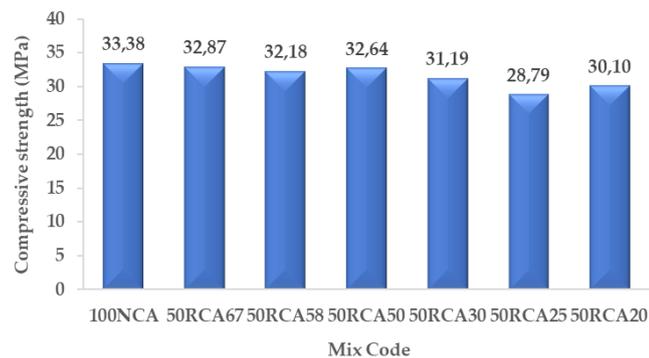

Figure 13. Compressive strength of concrete with 50% RCA.

Based on Table 5 and Figure 13, the compressive strength of NAC containing 100% NCA is higher than that of RAC containing 50% RCA. For RAC, compressive strength decreases as RCA quality decreases. The compressive strength of concrete incorporating 50% RCA with compressive strength classes of 67 MPa, 58 MPa, 50 MPa, 30 MPa, 25 MPa, and 20 MPa reached 98.47%, 96.41%, 97.78%, 93.42%, 86.25%, and 90.16%, respectively, of the compressive strength of concrete made with 100% NCA. These values are either higher or lower than those reported by Noshin et al. [28] of 94.26%. The analysis of variance (ANOVA) for 100% replacement of natural coarse aggregate (NCA) with recycled concrete aggregate (RCA) yielded an F-value of 10.541 with degrees of freedom (5,12) and a p-value of 0.00046, indicating that the quality of RCA has a statistically significant effect on the compressive strength of concrete when NCA is fully replaced by RCA. Similarly, for 50% replacement of NCA with RCA, the ANOVA yielded an F-value of 4.25 with degrees of freedom (5,12) and a p-value of 0.01863, indicating that the quality of RCA also has a statistically significant effect on the compressive strength of concrete at a 50% replacement level. The coefficient of determination, along with the regression equations for concrete compressive strength at 100% and 50% NCA replacement levels, is presented in Figures 14 and 15.
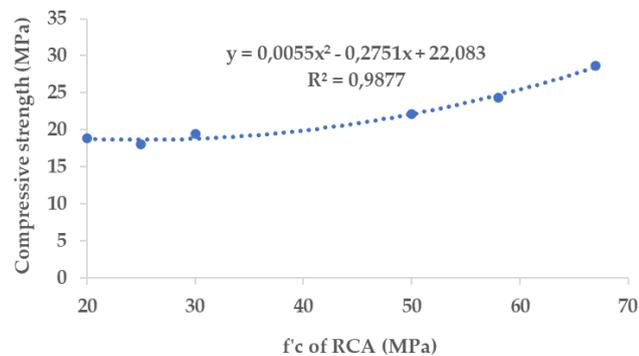

Figure 14. The coefficient of determination for **the** compressive strength of concrete with 100% RCA.

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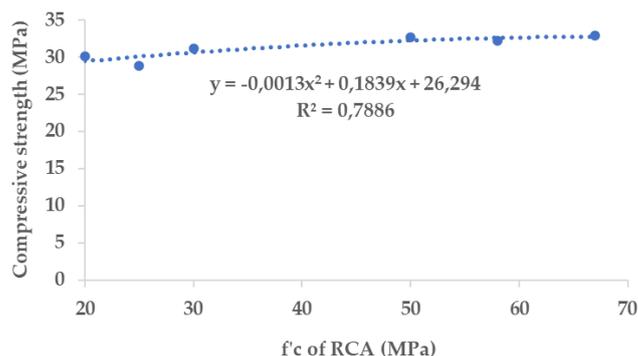
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Figure 15. The coefficient of determination for **the** compressive strength of concrete with 50% RCA.

From Figure 14, the high coefficient of determination ($R^2 = 0.9877$) indicates a statistically strong relationship between RCA quality and concrete compressive strength for mixtures with 100% replacement of NCA, where 98.77% of the variability in compressive strength is explained by the regression model $y = 0.0055x^2 - 0.2751x + 22.083$. From Figure 15, the coefficient of determination ($R^2 = 0.7886$) indicates a statistically strong relationship between RCA quality and concrete compressive strength for mixtures with 50% replacement of NCA, where 78.86% of the variability in compressive strength is explained by the regression model $y = -0,0013x2 + 0,1839x + 26,294$.

3.4 Unit weight

The unit weight results are presented in Figure 16. As shown, the unit weight of NAC made with 100% NCA is higher than that of RAC produced with either 100% or 50% RCA.
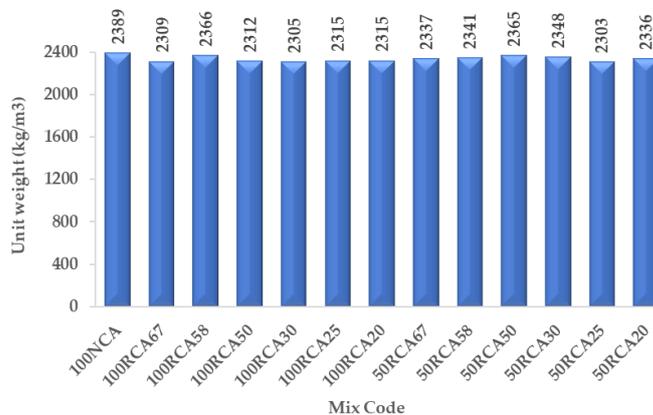

Figure 16. Unit weight.

The analysis of variance (ANOVA) for 100% replacement of natural coarse aggregate (NCA) with recycled concrete aggregate (RCA) yielded an F-value of 0.91 with degrees of freedom (5,12) and a p-value of 0.50623 ($p > 0.05$), indicating that the quality of RCA does not have a significant effect on unit weight. Similarly, for 50% replacement of NCA with RCA, the ANOVA yielded an F-value of 1.117 with degrees of freedom (5,12) and a p-value of 0.40191 ($p > 0.05$), indicating that the quality of RCA does not have a significant effect on unit weight at a 50% replacement level.

4. Conclusions

This research examines the effect of RCA quality when used as a substitute for NCA on concrete compressive strength. The findings demonstrate that NAC produced entirely with NCA achieves higher compressive strength than RAC incorporating 100% or 50% RCA. Furthermore, the compressive strength of RAC declines proportionally as the quality of RCA decreases. Statistical evaluation confirms that RCA quality

significantly influences the compressive strength of concrete at both 100% and 50% replacement levels. To achieve the minimum compressive strength of 20 MPa for structural concrete, a minimum RCA quality of 50 MPa is required for full NCA replacement, while a minimum RCA quality of 20 MPa is adequate for 50% replacement. Suggestions for further research include using a wider range of RCA quality levels and increasing the number of test specimens for each variation to improve the statistical robustness and reliability of the results.

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

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