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Investigation of Compressive and Flexural Strength Behavior of Recycled Aggregate Concrete for Structural Applications

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ABSTRACT

The construction sector produces large amounts of construction and demolition (C&D) waste annually, and at the same time consumes natural aggregate resources required to make new concrete. Recycled Aggregate Concrete (RAC) is a concrete type that is currently being discussed as a way to achieve sustainable construction by replacing natural coarse aggregate with processed C&D waste. This work examines the compressive and flexural strength behavior of concrete that is manufactured using recycled coarse aggregate (RCA) at 0, 25, 50, 75 and 100 weight percentages of natural coarse aggregate. Concrete specimens were cast and allowed to dry as per the ASTM standards and were tested at 7 days and 28 days of compressive strength, flexural strength, and water absorption at 28 days. Findings show that the mechanical strength steadily decreases with the concentration of RCA as a result of the residual mortar attached to the recycled particles and as a consequence of the weaker interfacial transition zone (ITZ). Compressive strength declined by about 30 percent compared to the control mix at 100 percent replacement and flexural strength declined by about 33 percent. But, at a maximum replacement of 2530 percent, the strength deterioration was still within a reasonable structural tolerance of 58 percent, indicating that RAC can be utilized in structural applications with reasonable design compromises at moderate replacement proportions. The results justify the wider use of RAC as an ecologically sound and structurally viable substitute to traditional concrete.

Keywords: Compressive and Flexural Strength Behavior, Recycled Aggregate Concrete (RAC), Structural Application

Introduction

The high rate of urbanization and development of infrastructure has resulted in the world experiencing an unprecedented amount of construction and demolition waste that is putting a strain on the landfill capacity and the extraction of natural resources. At the same time, the exploitation of natural high-quality sources of aggregates around cities has increased the cost of concrete manufacturing to the environment and economy. Recycling the demolished concrete into recycled coarse aggregate (RCA) is a two-fold solution: recycling will not only remove the waste materials in the landfills but also minimise the extraction of virgin aggregate.

Recycled Aggregate Concrete (RAC), has thus been a research topic that has received

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increased research over the last 20 years. Initial research determined the basic behavior of RAC and has shown that its mechanical performance is normally worse than that of natural aggregate concrete (NAC) of the same mix design (Hansen, 1992). Recycled aggregates are less dense than natural aggregates because of the layer of old cement mortar that is stuck to the surface and this makes them more porous, absorb more water and less strong and dense (Etxeberria et al., 2007; Padmini et al., 2009).

Although this performance disparity exists, engineers have not been keen on specifying RAC to structural components because there is no standardized design advice, and they are not confident about the long-term viability of this material (Rao et al., 2007). This hesitation is despite the fact that several studies have indicated that RAC is capable of attaining the strength levels that could be used in structural applications at moderate replacement ratios and that the mix design should be readjusted (Kou and Poon, 2012; Cantero et al., 2018).

The objective of this research is to thoroughly test the behavior of compressive and flexural strength of RAC with a complete replacement ratio (0-100% replacement) and determine a realistic replacement limit within which RAC can be employed in structural design without affecting the safety margin in design.

Research Objectives

(1) To assess how replacement ratio of RCA affect compressive strength of concrete at 7-days and 28-days. (2) To determine the flexural strength behaviour of RAC at different replacement levels. Objective (3) To identify the dependence between water absorption of RAC and decrease in strength. (4) To suggest an ideal RCA replacement ratio to be used in the structural work.

Literature Review

RAC mechanical behavior is well covered in the literature. One of the first detailed studies on uniaxial compressive behavior of RAC was performed by Xiao et al. (2005) who discovered that stress-strain behavior worsens gradually with the content of recycled material, which is mostly caused by the microcracking formed during the demolition and crushing process. On the same note, Rahal (2007) documented that the compressive and flexural strengths of concrete made using 100 per cent. recycled coarse aggregate showed a decrease of about 10-15% that of natural aggregate concrete of the same mix proportions.

The interfacial transition zone (ITZ) has been found to play a major role in determining the loss of RAC strength. Poon, Shui and Lam (2004) have shown that the old ITZ between the original aggregate and adhered mortar along with a new ITZ between the recycled particle and new cement paste forms a dual-interface weakness characteristic of RAC. Tam, Gao and Tam (2005) suggested a two-stage mixing method to partially overcome this shortcoming as a way of enabling partial pre-coating of recycled aggregate with cement paste and then mixing fully after which they reported strength gains of up to 20 percent compared to single-stage mixing.

The absorption of water is always indicated as one of the most important indicators of the quality of RAC. De Juan and Gutiérrez (2009) established positive correlation between percentage of attached mortar on recycled aggregate and its water absorption capacity which in turn influences the effective water- cement ratio during hydration.

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Padmini et al. (2009) affirmed that aggregates obtained with parent concrete which has high strength yields a relatively high mechanical performance of RAC, and that the source concrete quality is significant in the production of RAC.

There are some experiments that have measured strength loss over replacement ratios. Etxeberria et al. (2007) reported decreases in compressive strength of about 20-25 percent at 100 percent RCA replacement and Kou and Poon (2012) reported surface modification of recycled aggregates with pozzolanic coating enhanced compressive strength and durability. The use of statistical and numerical modeling by Jayasuriya, Adams and Bandelt (2018) proved that RAC mechanical properties are more variable than NAC, which is why larger samples are required in the quality control of RAC. Cantero et al. (2018) also established that the variability in the source material of recycled aggregates has a statistically significant effect on physical-mechanical concrete properties.

Behavior in terms of durability has also been addressed. Limbachiya, SeddikMeddah and Ouchagour (2012) assessed Portland/silica fume cement concrete produced using RCA and results showed that the addition of supplementary cementitious materials significantly enhanced chloride resistance even in the presence of porous nature of recycled aggregate. Both Beltran et al. (2014) and Bravo et al. (2015) found that cement additions could partially compensate strength losses in RAC to enable the use of recycled concretes in medium-quality structural applications. Similar results were obtained by Gonzalez-Fonteboa and Martinez-Abella (2008) who demonstrated that the incorporation of silica fume increased the mechanical properties of demolition-waste concretes.

Studies in the region that pertain to Pakistan are important background. In a study undertaken with the local aggregate sources, Ahmad et al. (2022) noted compressive strength losses of 3.8, 5.7, 12.9, and 15.8 at 25, 50, 75, and 100 percentile RCA replacement, respectively, which revealed results that were largely in line with the global literature. Umer et al. (2024) investigated cement-less RAC mixes with activators through alkaline solutions as a sustainable construction option in Pakistan, with the best compressive strength improvement of up to 40 percent in cement-less mixes at optimized activator molarity compared to the control cement-less mixes. Khan et al. (2022) used machine learning, such as gradient boosting and decision tree algorithms, to forecast RAC compressive strength based on mix design parameters, with high prediction accuracy and replacement ratio given as the most significant parameter.

Long-term durability and shrinkage are also well-regarded. An overview of the shrinkage behavior was synthesized by Silva, de Brito and Dhir (2015) across several RAC studies and the authors concluded that the replacement ratio positively affected shrinkage as a result of a greater paste content needed to offset aggregate porosity. A related review, Silva et al. (2015) investigated carbonation behaviour in RAC and concluded that carbonation depth increased with RCA content, but this can be overcome by reducing water-cement ratios. Verian, Ashraf and Cao (2018) thoroughly reviewed the properties of RCA and their impact on the new concrete production, supporting the agreement that the quality of RCA is the main lever of enhancing RAC performance. Malešev, Radonjanin and Marinkovic (2010) have found that replacement of up to 50 percent or less can be reliably used to attain

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structural-grade strength with RAC, which is also reflected in much of the literature reviewed. Taken together, this accumulation of studies makes RCA replacement ratio, parent concrete quality and water-cement ratio management the three most influential factors that define structural feasibility of RAC.

Materials and Methodology

Materials

Ordinary Portland Cement (OPC) was used as well as locally available natural coarse aggregate (crushed stone, 20 mm maximum size), natural river sand as fine aggregate and recycled coarse aggregate (crushed waste concrete, demolished structural elements). Aggregate was also recycled and sorted manually without contamination (brick, wood, plastic) before being crushed, which is a recommended practice (RILEM TC 121-DRG, 1994; de Brito &Saikia, 2013). The mixing curing was done with potable water that meets ASTM C1602.

Mix Design

The natural coarse aggregate was substituted with recycled coarse aggregate at 0% (control), 25, 50, 75, and 100 percent by weight in five concrete mixes as per the requirements of ASTM C33/C33M (2018) on aggregate grading. All mixes had a constant water-cement ratio of 0.45 and constant cement content of 380 kg/m 3 in order to remove the influence of replacement ratio. The proportions of the mix are summarized in Table 1.

Table 1: Concrete Mix Proportions

Mix ID	RCA Replacement (%)	Cement (kg/m³)	Natural CA (kg/m³)	Recycled CA (kg/m³)	w/c Ratio
M-0	0	380	1100	0	0.45
M-25	25	380	825	275	0.45
M-50	50	380	550	550	0.45
M-75	75	380	275	825	0.45
M-100	100	380	0	1100	0.45

Specimen Preparation and Curing

ASTM C192 specimens were produced by casting 150 mm cube specimens to test compressive strength and 100 × 100 × 500 mm prisms to test flexural strength. After 24 hours, all the specimens were demolded and water-cured at 23 ± 2 C up to the respective ages of testing 7 and 28 days.

Testing Procedures

The compressive strength was obtained as defined in ASTM C39/C39M (2021) with a calibrated universal testing machine at a known loading rate. The three-point loading method was used to measure flexural strength according to ASTM C78/C78M (2022). Water absorption was determined using the saturated surface-dry technique outlined in ASTM C642, as well as procedures in other previous RAC durability investigations

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(Silva et al., 2015). For each mix and test age, three specimens were tested and the average value reported.

Results and Discussion

The results of Table 2 provide an overview of the average compressive strength, flexural strength, and water absorption of each mix.

Table 2: Summary of Test Results

Mix ID	7-Day Compressive Strength (MPa)	28-Day Compressive Strength (MPa)	28-Day Flexural Strength (MPa)	Water Absorption (%)
M-0	22.4	34.8	4.6	1.8
M-25	21.1	32.9	4.3	2.6
M-50	19.6	30.1	3.9	3.7
M-75	17.8	27.0	3.5	4.9
M-100	15.9	24.3	3.1	6.2

Effect of RCA Replacement on Compressive Strength

The compressive strength declined gradually with rise in RCA content at 7 and 28 days. The control mix (M-0) had a 28-day strength of 34.8 MPa, and the completely-replaced mix (M-100) had a strength of 24.3 Mpa, a 30-percent less strength. The trend is in line with the results of the studies by Xiao et al. (2005) and Rahal (2007) who explained the same cuts by the less effective ITZ and the increased porosity due to the adhered mortar on the recycled particles. It is important to note that strength loss was also modest (5.5) until the 25 percent replacement amount and thus the commonly used 25-30 percent replacement ratio as safe replacement ratio of structural-grade concrete was found not to need significant modification of mix design (Malešev et al., 2010).

Effect of RCA Replacement on Flexural Strength

The flexural strength adopted the same decreasing pattern wherein it decreases between 4.6 Mpa at 0 percent replacement to 3.1 Mpa at 100 percent replacement, a decrease of about 33 percent. This percentage-wise reduction reflects the compressive strength trend and agrees with those of Etxeberria et al. (2007) and Bravo et al. (2015) who observed that flexural performance is especially sensitive to the bond strength between recycled aggregate and neighboring paste. The flexural strength reduction rate was a little more acute than compressive strength reduction after a 50 percent replacement level, indicating that flexural members with high RCA content might need further reinforcement design consideration.

Water Absorption and Durability Implications

The degree of water absorption rose by 1.8 percent in the control mix and 6.2 percent at full replacement; this is more than three times higher. This observation is in line with the established relationship between attached mortar content and water

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absorption capacity (De Juan & Gutiérrez, 2009). The strength decrease directly correlates with increased absorption because the more the absorption, the more internal porosity and less dense a microstructure a material has, both of which undermine load-bearing capacity and long-term durability (Gonzalez-Fonteboa& Martinez-Abella, 2008).

Discussion and Practical Implications

The findings confirm that the decrease in RAC strength is dependant on the RCA replacement ratio, but also indicate that the decrease is not so great to exclude structural application at moderate replacement rates. The compressive strength loss (5.5) at 25% replacement is well within the normal structural design safety margin, which is in line with recommendations by Malešev, Radonjanin and Marinkovic (2010) and Beltran et al. (2014), who both suggested that loss of strength at these replacement levels can be further mitigated by cement content modifications. In applications with a greater replacement ratio (50% and more), additional cementitious materials (silica fume or fly ash), aggregate surface treatment, or the two-stage mixing method suggested by Tam, Gao and Tam (2005) should be used to restore more mechanical performance similar to that of conventional concrete.

The findings are especially applicable to the Pakistani construction setting, where local research (Ahmad et al., 2022; Umer et al., 2024) has also demonstrated similar trends in strengths with the use of locally sourced demolition waste, which further supports the possibility of RAC implementation in developing infrastructure markets where both aggregate scarcity and the increasing volumes of C&D waste are considered.

Conclusion

In this experiment, the compressive and flexural strength behavior of recycled aggregate concrete at various replacement ratios of 0-100 were examined. They are concluded as follows: (1) Compressive and flexural strength both decrease steadily with replacement percentage of the RCA with about 30 and 33 percent reductions respectively at 100 percent replacement. (2) The strength loss is not exceeded by more than acceptable structural tolerances (less than 8%) up to 25% replacement and this ratio is a sensible recommendation to use in structural applications without a major mix redesign. (3) RCA content enhances water absorption significantly, which is also a good early predictor of anticipated strength and durability performance. (4) To achieve higher replacement ratios, additional cementitious materials and methods of aggregate treatment are suggested to maintain structural-grade performance. Altogether the results show that RAC can be used viably in structural construction, especially in moderate replacement levels, to help in building practices more sustainably and less reliant on natural aggregate resources. The future research in this area should be on long-term durability when exposed to regional climatic conditions and local design codes to use RAC in Pakistan.

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