



EXPERIMENTAL INVESTIGATIONS ON RECYCLED CONCRETE WITH FLYASH AND RCA

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Abstract: This study explored enhancing recycled aggregate concrete (RAC) by using both recycled coarse and fine aggregates, with fly ash partially replacing cement. After adjusting the recycled aggregates for continuous gradation, the effects of accelerated carbonation on RAC's performance and microstructure were assessed using mercury intrusion porosimetry and SEM-EDS analysis. Results showed that carbonation increased RAC compressive strength by up to 13% and compacted its microstructure. Using 20% fly ash reduced carbon emissions by over 13%, supporting sustainable development. The optimal recycled fine aggregate content was found to be under 15% for best results.

Keywords: recycled coarse aggregate; recycled fine aggregate; accelerated carbonation; microstructure; carbon emission

1. Introduction

Climate records are continually being broken, and atmospheric CO₂ concentrations are reaching new highs. With global temperatures nearing the 1.5°C limit outlined in the Paris Agreement, the IPCC has urged countries to achieve net-zero CO₂ emissions by 2050. In response, China announced its "dual-carbon" targets, aiming for peak emissions by 2030 and carbon neutrality by 2060 [1]. Achieving these goals demands carbon reduction across all sectors, including urban construction. Urbanization is accelerating; by 2050, 68% of the global population is expected to reside in cities, amplifying the demand for construction materials like concrete. Traditional concrete production relies heavily on OPC, consuming vast amounts of sand and gravel and emitting significant CO₂, with 0.8–1.0 tons of CO₂ per ton of OPC produced. China's annual construction waste, over 3 billion tons (50–60% concrete), underscores the unsustainable nature of current practices [2].

Fly ash (FA), a byproduct of coal-fired power, offers a sustainable alternative. China generated about 827 million tons of FA in 2021, which requires substantial storage and causes ecological harm. Reusing



FA in concrete can mitigate these issues. Research shows that replacing OPC with FA can enhance concrete's durability and mechanical properties when FA content is below 30%, while also reducing CO₂ emissions due to the material's unique pozzolanic and microaggregate effects. Research on the reuse of demolished concrete has shown that substituting natural aggregates with recycled aggregates (RCA and RFA) can reduce resource extraction and aid in managing construction waste, promoting sustainable practices. For example, Belabbas et al. found that RCA use at elevated curing temperatures had negative effects on recycled concrete's mechanical properties, while Ma et al. reported that RFA modified with sodium silicate improved compressive strength in recycled mortar by up to 13% when kept below a 30% replacement rate. However, old mortar attached to recycled aggregates can weaken performance. Studies suggest that managing the residual paste on RFA can mitigate this impact [3].

Currently, most recycled concrete research focuses on RCA or RFA from building demolition, while road demolition waste is typically used in non-structural applications due to its high porosity and unsuitable grading for building projects. Improving recycled aggregates from road demolition could expand their use in construction engineering. Concrete durability is also influenced by CO₂ exposure, which can corrode embedded steel and decrease alkalinity over time [4]. However, carbonation reactions improve concrete compactness and allow some carbon sequestration by transforming hydration products like Ca(OH)₂ into CaCO₃. Life cycle assessment (LCA) is effective for assessing the carbon footprint of concrete through its lifespan, factoring in environmental impacts from production to end-use.

This study uses RCA and RFA from road waste, supplemented with fly ash (FA) in place of OPC, to create FA recycled aggregate concrete (FARAC). It evaluates the effects of accelerated carbonation on FARAC's carbonation depth, compressive strength, and microstructure, alongside an LCA analysis to track emissions at different stages, supporting FARAC's potential practical use in construction with tailored carbon reduction strategies [5].

2. Materials and Experimentation

2.1.1 Binders

The binders included Class F fly ash (FA) with less than 10% CaO and ordinary Portland cement (OPC, P·O 42.5). The FA and OPC were analyzed for chemical composition, particle size distribution, and X-ray diffraction (XRD) patterns [6].

2.1.2 Aggregates

Natural coarse aggregate (NCA) was gravel, while natural fine aggregate (NFA) was river sand. Recycled aggregates were obtained from a highway reconstruction project in Xinjiang. Due to the gap-graded distribution of the recycled coarse aggregate (RCA), the particles were re-sieved to ensure a continuous gradation that met standards [7].

2.1.3 Other Materials

A polycarboxylate superplasticizer (PS) was used as a water reducer with a reduction rate of at least 25%, and tap water from Urumqi was used for mixing [8].

2.2 Mix Design



The FARAC mix was designed per relevant standards, with FA contents at 0%, 10%, and 20%, RCA replacement rates at 0%, 50%, and 100%, and RFA replacement rates at 0%, 15%, and 30% [9].

2.3 Specimen Preparation

Concrete was mixed with a forced single horizontal shaft mixer, then placed in 100 mm³ molds that were pre-treated with oil. After vibration to remove air bubbles, specimens were cured at $(20 \pm 2)^\circ\text{C}$ with over 95% humidity after demolding [10].

2.4 Testing Methods

For accelerated carbonation testing, specimens were dried, sealed on four sides with paraffin, and exposed in a carbonation chamber. Compressive strength testing was done using an electro-hydraulic servo press [11].

3. Experimental Results

3.1 Carbonation Depth

The carbonation depth was measured by spraying phenolphthalein solution and assessing every 10 mm. The addition of fly ash (FA) and recycled aggregate increased the carbonation depth over time, although the growth rate slowed gradually. The samples with 20% FA showed higher carbonation depths compared to those with 10% FA, as FA reduces the formation of calcium hydroxide, thus lowering concrete alkalinity and initial carbonation resistance. Over time, however, carbonation reaction products fill voids, slightly improving resistance.

Higher RCA and RFA replacement rates also increased carbonation depth. The porosity of the recycled fine aggregate (RFA) significantly impacted this, as the smaller particle size and attached old paste made it easier for CO₂ to permeate. For example, increasing RFA from 15% to 30% raised carbonation depth more significantly than increasing RCA from 50% to 100% [12].

3.2 Compressive Strength (UCS)

UCS was measured after 28 and 56 days of curing, with some samples undergoing additional carbonation. For samples without FA, UCS increased over time; however, the UCS of specimens with 20% FA surpassed those with lower FA content only at later stages due to delayed hydration effects of FA filling internal pores.

The UCS benefits of carbonation were more pronounced in samples with recycled aggregates, as old mortar on recycled particles allowed deeper CO₂ penetration, enhancing the carbonation reaction. For samples with 20% FA, UCS increased by up to 13.6% after carbonation. However, excessive recycled aggregate replacement ultimately decreased UCS. Optimal replacement rates were 50% for RCA and 15% for RFA to balance carbonation strength gains and recycled aggregate effects [13].

3.3. Microstructure Characteristics

3.3.1 MIP Analysis of Pore Structure

Pore size distribution in concrete directly impacts its mechanical strength and durability. Concrete pores are categorized into four types by size: harmless (<20 nm), less harmful (20-50 nm), harmful (50-200



nm), and more harmful (>200 nm). In this study, accelerated carbonation's effect on the pore structure of fly ash and recycled aggregate concrete (FARAC) was analyzed through mercury intrusion porosimetry (MIP) tests on both carbonated and uncarbonated samples.

Accelerated carbonation was found to significantly reduce porosity across all sample groups. In non-FA concrete (FA0C0F0), porosity decreased by 39.12% after carbonation, while a similar sample with 10% FA (FA10C0F0) showed a 26.47% reduction. This effect intensified as recycled aggregate content increased. For example, FA10C100F30, containing 100% RCA and 30% RFA, saw the highest porosity reduction of 43.2%. These changes are consistent with the observed increase in unconfined compressive strength (UCS) after carbonation.

Accelerated carbonation also altered pore structure by making pore distributions more uniform and reducing the distinct threshold diameter seen in uncarbonated samples. As carbonation progressed, CO₂ filled microvoids and microcracks with calcite, resulting in a shift in pore size distribution. The original medium-sized pores were replaced by a higher proportion of harmless and larger pores, moving the most probable pore diameter from the harmful to the harmless range. However, in some samples (e.g., carbonated FA10C0F0 and FA10C100F15), a notable peak appeared in both harmless and more harmful pore regions, suggesting that carbonation-induced micro-defects may create larger, interconnected pores. This shift in pore structure due to carbonation enhances the mechanical properties and durability of FARAC [14].

4. Carbon Emission Analysis of FARAC

Compared to ordinary concrete, FARAC offers enhanced environmental benefits. This study quantitatively assesses these benefits through a life cycle assessment (LCA) focusing on carbon emissions. Zhang et al. examined the hydration reactions of binders with varying FA levels, deriving a formula to correlate the hydration degree of OPC and FA with the water-binder (w/b) ratio, which aids in calculating carbon emissions for FA-based concrete. developed a carbonation-absorption model specific to recycled concrete and performed an LCA-based environmental assessment. Buildin carbon emission model, this study incorporates FARAC into an established LCA framework for recycled concrete, enabling a detailed analysis of FARAC's carbon footprint and environmental impact.

Table 1. Parameters related to m_0 and x_c .

Group	βf	$gRCA$	$gRFA$	γc	C	m_0	x_c
	(%)	-	-	-	(kg)	(kg)	(mm)
FA0C0F0	0	1	1	1	488	3408	3.25
FA10C0F0	10	1	1	0.9	439	2886	5.79
FA10C50F15	10	1.25	1.25	0.9	439	2886	9.04
FA10C50F30	10	1.25	1.5	0.9	439	2886	10.85
FA10C100F15	10	1.5	1.25	0.9	439	2886	10.85
FA10C100F30	10	1.5	1.5	0.9	439	2886	13.02



FA20C0F0	20	1	1	0.8	390	2363	8.86
FA20C50F15	20	1.25	1.25	0.8	390	2363	13.84
FA20C50F30	20	1.25	1.5	0.8	390	2363	16.61
FA20C100F15	20	1.5	1.25	0.8	390	2363	16.61
FA20C100F30	20	1.5	1.5	0.8	390	2363	19.94

From the experimental results mentioned earlier, it is evident that the RFA has a more significant impact on the carbonation resistance of the FARAC compared with the RCA.

When the replacement rate of the RFA is zero, g_{RFA} is taken as one, and when the replacement rate is 30%, g_{RFA} is taken as one and five-tenths. For the intermediate replacement rates, the value is determined by linear interpolation. The calculations for m_0 , x_c , and related parameters can be found in Table 1.

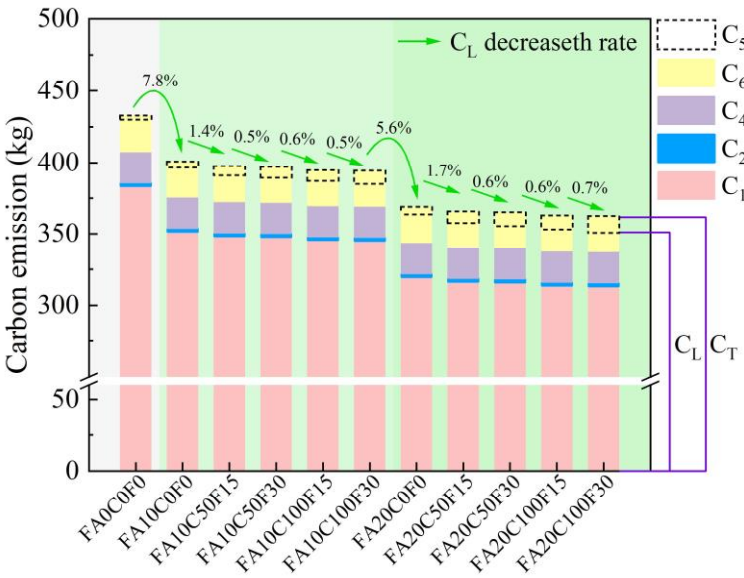


Figure 1. Carbon emissions of 1 m³ of FARAC.

Figure 1 illustrates that as the replacement rate of recycled aggregate increases, the value of rises accordingly. Due to their high porosity and the mortar adhered to their surface's, recycled aggregates are more effective at sequestering carbon than natural aggregates. Furthermore, carbonation improves the performance of these recycled aggregates, supporting sustainable and eco-friendly development efforts [14,55]. However, a key issue to consider is that accelerated carbonation can make the concrete more neutral, which in real-world conditions may lower the pH and accelerate the corrosion of internal steel reinforcement, ultimately impacting the structure's durability [15].

5. Conclusions

The study explored the carbonation resistance and strength enhancement of fly ash and recycled aggregate concrete (FARAC) under accelerated carbonation, focusing on the roles of fly ash (FA), recycled coarse aggregate (RCA), and recycled fine aggregate (RFA) through carbonation depth,



compressive strength, and carbon emissions analysis. It was found that increasing the FA content and recycled aggregate replacement led to a higher carbonation depth, with the FA20C100F30 mix showing an 118% increase in carbonation depth compared to FA0C0F0 after 28 days, although the growth rate slowed over time. The accelerated carbonation also enhanced the compressive strength of FARAC, with higher FA and recycled aggregate contents showing more pronounced strengthening effects. Specifically, mixes like FA20C50F15, FA20C50F30, FA20C100F15, and FA20C100F30 exhibited strength increases up to 13.92%. Microscopic analysis revealed that carbonation improved FARAC's internal structure by significantly reducing porosity and refining the pore size distribution, with SEM-EDS images showing a denser concrete matrix. Moreover, the use of FA and recycled aggregates contributed to reduced carbon emissions, with the LCA emissions of FA20C50F15 decreasing by 16.9% compared to conventional concrete. The optimal FARAC mix, balancing both performance and sustainability, was found to be 20% FA, 50% RCA, and 15% RFA. The study highlights that FARAC offers significant environmental and resource-saving benefits by repurposing road demolition waste, and suggests that future research should focus on its mechanical properties and durability under various adverse conditions. Further exploration into integrating FARAC with artificial intelligence, smart construction, and machine learning could unlock additional potential applications.

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