EFFECT OF TREATED RECYCLED AGGREGATE IN CONCRETE

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ABSTRACT

The reduction in natural aggregate availability and the rising volume of construction waste have heightened the need for sustainable materials, particularly recycled aggregate concrete (RAC). However, recycled aggregates (RA) often exhibit high porosity, a bonded mortar, and a weak interfacial transition zone (ITZ), which undermine the performance of concrete. This paper assesses the impact of combined mechanical abrasion, acid washing, and fly-ash coating on recycled concrete aggregates (RCA) to improve their structural efficiency and microstructural integrity. Concrete mixes were prepared by substituting natural coarse aggregates (NCA) with treated RCA at 0, 20, 50, 80, and 100% replacement levels, using a 1:2:4 mix ratio and a water-to-cement ratio of 0.50. The treatment process included mechanical abrasion, immersion in 1% H_2SO_4, and coating with fly-ash slurry. Slump, compressive, and tensile strength tests were conducted to evaluate the mechanical properties of the concrete at 7 and 28 days, in accordance with ASTM standards. The results showed that fly-ash-treated RCA exhibited a significant improvement in workability (18-28%), a 25% decrease in water absorption, and an 8% increase in aggregate density. Compressive strength increased to 13-14.6 MPa at 50% treated RCA (TRA), up from 11-12 MPa, and tensile strength rose to 7.2 MPa. The fly-ash treatment facilitated a pozzolanic reaction, resulting in the development of a secondary calcium-silicate-hydrate (C-S-H) gel that localized ITZ density and enhanced bonding between the cement paste and aggregates. The TRA replacement range of 20-50% was found to achieve optimal strength and life cycle, providing performance comparable to that of conventional concrete. The results indicate that combining RCA with mechanical, chemical, and fly-ash technologies provides a viable and environmentally sustainable solution for producing high-performance, low-carbon concrete. These outcomes support the objectives of sustainable infrastructure development and circular construction.

Keywords: *Recycled aggregate; Treated aggregate; Fly ash; Concrete strength; Sustainability.*

1.INTRODUCTION

Concrete is a construction material that has been in the market in the most significant proportion worldwide, with an annual production exceeding 10 billion tons. Nevertheless, this widespread application is also a major contributor to environmental issues, including the consumption of natural aggregates (NA), energy-intensive usage, and the generation of waste products from demolished constructions. (Güneyisi et al., 2014; Huang et al., 2024). The mining of NA in rivers and quarries leads to habitat devastation, groundwater contamination, and massive carbon emissions resulting from transportation and processing. Hence, there is an increased urgency for sustainable alternatives, such as recycled aggregate concrete (RAC). The recycled construction and demolition waste forms the recycled concrete aggregates (RCA) used in RAC to offer a sustainable alternative, which advances the principles of the circular economy by reducing reliance on virgin resources (Shuvo et al., 2022).

Although recycled aggregates (RA) have a positive environmental effect, they have several intrinsic disadvantages, such as a high porosity rate (approximately 6.8%), higher water absorption, and reduced bulk density (approximately 1420 kg/m3), thereby yielding lower mechanical properties and lower durability than natural aggregates (Khanapur et al., 2025; Savva et al., 2021). The fact that RCA has adhered mortar poses a significant obstacle since there is a weak interfacial transition zone (ITZ) between the old and new cement paste. This ITZ is likely to contain microcracks, voids, and unhydrated particles, which result in decreased bond strength, stiffness, and structural integrity. As a result, concrete made using untreated RA suffers a 20-30 percent compressive strength loss when compared to conventional concrete made using natural aggregates (Alqarni et al., 2022; Limbachiya et al., 2000).

In order to address these shortcomings, resistance to surface texture, density, and compatibility of RA needs to be increased by using proper methods of treatment. The different treatments that have been suggested include mechanical scrubbing, acid washing, and fly-ash coating, which have demonstrated the most significant potential of enhancing the performance of RCA (Forero et al., 2022; Ismail & Ramli, 2013). Mechanical scrubbing is used to clean loosely bonded mortar and enhance the texture of the aggregate. In contrast, calcium hydroxide is dissolved by acid treatment (e.g., immersion in 1% H2SO4), which helps increase density and decrease water absorption. This is because fly-ash coating is the most sustainable and effective treatment, as it combines the benefits of pozzolana with chemical stabilization. An application like a slurry causes fly ash to occupy surface micro-voids. During hydration, it reacts with calcium hydroxide to form secondary calcium-silicate-hydrate (C-S-H) gel, which densifies the ITZ and enhances the bond between the aggregate and the cement paste. (Balasubramani & Palaniappan, 2025; Peiris et al., 2025). Additionally, it enhances the mechanical strength and ductility of the concrete; the treatment also reduces the permeability and long-term shrinkage of the material, making the concrete more durable.

This experimental research investigates the use of recycled concrete aggregates (RCA) subjected to mechanical abrasion, acid washing, and fly-ash coating. Five concrete blends with RCA replacement (0, 20, 50, 80, and 100% of natural coarse aggregates (NCA) were prepared using a 1:2:4 mix proportion and a water-to-cement ratio of 0.50. The treatment sequence included mechanical abrasion, immersion in a 1% H_2SO_4 solution, and coating with a fly-ash slurry. Characterization of mechanical properties was conducted, including slump, compressive strength, and tensile strength, as per ASTM C143, C39, and C496 at 7 and 28 days. Results showed that fly-ash-treated RCA exhibited significant performance improvements: slump increased by 18-28 percent, compressive strength rose by 11-12 MPa to 13-14.6 MPa, and tensile strength, initially 5.3 MPa, increased to 7.2 MPa at 50% replacement. The results indicate increased cohesion, a more compact microstructure, and improved bonding at the ITZ, demonstrating that optimized surface treatment can produce high-performance, environmentally friendly RAC that matches the properties of natural-aggregate concrete. (Ahmed et al., 2021; Kępniak et al., 2025).

This study aims to evaluate the effectiveness of a combined treatment approach, comprising mechanical scrubbing, acid washing, and fly ash coating, in enhancing the mechanical properties of recycled aggregate concrete. The research demonstrates that the mechanical properties of treated RCA, even when used in up to 50% replacement, are comparable to those of conventional concrete and that the environmental impact is significantly reduced. The findings offer a feasible, large-scale strategy for manufacturing high-performance, sustainable building materials, particularly in structural construction, in areas with an abundance of building and demolition waste (Korjakins et al., 2024).

2.MATERIALS & METHODS

2.1 Materials

2.1.1 Cement

In this study, Ordinary Portland Pozzolana Cement (PPC) that met ASTM C150 and was equivalent to CEM II/B-P 42.5N was used. The cement was also ordered in a single batch to ensure consistency. The Blaine fineness was approximately 340 m^2/kg, and the specific gravity was 3.15. PPC was chosen because it is a pozzolanic compound that reacts with calcium hydroxide (CH) to produce secondary calcium silicate hydrate (C-S-H). It enhances the strength of concrete and lowers the porosity, which increases its durability and microstructure (Güneyisi et al., 2014; Huang et al., 2024). The PPC pozzolanic property is also beneficial in terms of long-term strength and, as such, would be ideal for sustainable concrete.

2.1.2 Fine Aggregate

The superfine aggregate was clean Sylhet River sand, which contained no organic impurities or clay, thereby ensuring the high quality of the concrete. It met the ASTM C33 grading standards, and its fineness modulus (FM) was 2.65, and its bulk density was 1680 kg/m3. The maximum length of the particles was capped at 4.75 mm, according to the standard guidelines. To eliminate any moisture content in the sand before use, it was oven-dried at 105 ± 5 °C over 24 hours to ensure the sand had homogeneous mixing properties in the concrete. This process was used to eliminate any water discrepancies during the curing and hydrating processes (Khanapur et al., 2025; Savva et al., 2021).

2.1.3 Coarse Aggregate

Two types of coarse aggregates were used:

- Natural Coarse Aggregate (NCA): Crushed chips of bricks used in the area that have a size of between 10 and 20 mm.
- Recycled Coarse Aggregate (RCA): It was obtained as the result of demolished reinforced concrete structural elements in the city of Dhaka. It ensured that the parent concrete had a compressive strength of 20-25 MPa, which is a standard range of structural grade concrete(Shuvo et al., 2022).

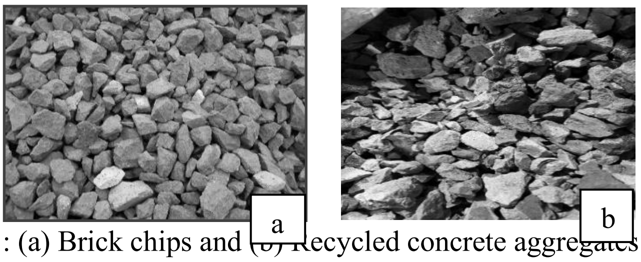

Figure 1: (a) Brick chips and (b) Recycled concrete aggregates (RCA).

RCA was thoroughly washed, air-dried, and sieved to match the size distribution of NCA. The preliminary testing revealed that RCA had a higher water absorption percentage (6.8%) and lower bulk density (1420 kg/m^3) than NCA (2.1% and 1610 kg/m^3, respectively). These results are consistent with earlier research, which has consistently found RCA to be more porous and absorb water due to its attached mortar and lower density compared to NCA (Khanapur et al., 2025; Limbachiya et al., 2000).

2.1.4 Water

Both mixing and curing were performed using clean potable water that met the ASTM C1602 criteria to maintain impurity-free hydration and ensure to uniform strength increase in all mixes of recycled-aggregate concrete (RAC). High-quality water reduces the chances of contamination that may disrupt the hydration process and eventually influence the mechanical properties of the concrete (Shuvo et al., 2022).

2.2 Treatment of Recycled Aggregates

Three RCA were subjected to three treatment methods in order to increase their structural and surface properties. Prior to use in concrete production. All the techniques were intended to minimize porosity, remove mortar with weak bonds, and increase the bonding capacity of the surface to enhance performance in the concrete mixes.

2.2.1 Mechanical Treatment

RCA aggregates were scrubbed mechanically in a rotary drum for 10 minutes to get rid of loose mortar attached to their surface. This process made the mortar that was adhered to become thinner by a factor of 15-20. Mechanical treatment is an effective method for thickening and reducing water absorption in RCA, which involves removing excess mortar and polishing the surface. It also improves the textural properties of the aggregate that positively influence the bonding of the aggregate and the cement paste in the final concrete (Peiris et al., 2025; Savva et al., 2021).

2.2.2 Chemical Treatment

RCA that had been treated with chemicals was immersed in 1% equivalent of sulfuric acid (H2SO4) and left to sit for 30 minutes. They were then washed with potable water and dried at 1050 °C over 24 hours. It is a selective method used to dissolve calcium hydroxide and weakly hydrolyzed products in the old mortar to increase the density and surface properties of the aggregate. The apparent density was found to increase by 8% and water absorption decreased by 25% compared to undressed RCA, which is a positive outcome of treatment to enhance the structural integrity of the aggregate (Güneyisi et al., 2014; Ismail & Ramli, 2013).

2.2.3 Fly Ash Coating Treatment

Mechanical cleaning was followed by RCA being placed in a fly ash slurry (fly ash to water ratio of 1:1 by weight) for 2 hours. The agglomerated aggregates were afterwards dried with air (24 hours) at 25-300 °C. The small fly ash particles plugged the surface pores, thereby enhancing the interfacial transition zone (ITZ) by creating a secondary C-S-H gel during the hydration process. This reaction enhances the connection between the aggregate and the cement paste, as well as enhancing the mechanical and durability strength. It is a suitable method to choose because of its environmental friendliness, low cost, and the ability to densify the material over the long term, which makes it a perfect solution to green construction (Huang et al., 2024; Ismail & Ramli, 2014).

2.3 Mix Design

A traditional 1:2:4 mix ratio (cement: fine aggregate: coarse aggregate) was used in this study, corresponding to M20-grade concrete with a w/c ratio of 0.50, as per the ASTM C192 standard. The coarse aggregate was partially or fully replaced with treated RCA at replacement levels of 0%, 20%, 50%, 80%, and 100% by weight. Weight-to-volume conversion factors were used to determine the mix proportions to accordance with ACI 211.1-91. This is an incremental approach of substitution, whereby many international studies have proposed this as a means of establishing the performance threshold of recycled aggregates (RA) when used in structures (Limbachiya et al., 2000; Shuvo et al., 2022; Tam et al., 2007).

Table 1: Mix proportions of recycled aggregate concrete (RAC).

Mix type	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Brick Chips (kg/m^3)	RCA (kg/m^3)
RA100	5.5	11	22	0	22
RA 80	5.5	11	22	4.4	17.6
RA 50	5.5	11	22	11	11
RA 20	5.5	11	22	17.6	4.4
RA 0	5.5	11	22	22	0

2.4 Specimen Preparation

The concrete was blended using a mechanical drum mixer, as specified in ASTM C192/C192M-21. Blending was performed for 30 seconds to mix the coarse and fine aggregates. Afterward, cement mixed with water was added gradually, taking approximately 2.5 minutes per batch in total. A total of nine cylindrical specimens (100 mm x 200 mm) that met ASTM C470/C470M in compressive and tensile tests were made in each batch. The molds were wiped clean with mineral oil and filled in three layers, using a 25 mm tamping rod and 25 blows. The surfaces were smoothed using polyethylene sheets to reduce moisture evaporation. The specimens were demolded and cured in water at 27 °C ± 20 °C after 24 hours ± 1 hour, and the testing lasted 7 and 28 days. Water was changed every 48 hours to maintain the conditions. A total of 45 cylinders were cast for five mix types **(**RA 0, RA 20, RA 50, RA 80 , and RA 100**).**

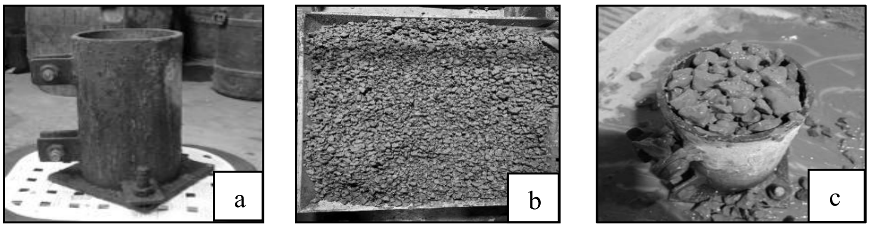

Figure 2: (a) Cylinder preparation (b) Mixing (c) Cylinder Casting

Testing was performed following ASTM C39/C39M for compressive strength and ASTM C496/C496M for splitting tensile strength. This approach guaranteed consistent compaction, curing, and reproducible results.

2.5 Testing Procedures

2.5.1 Fresh Properties Tests

2.5.1.1 Slump Test

The workability of fresh concrete was assessed using the slump test, as per ASTM C143/C143M-20 and BS EN 12350-2:2019 standards. A standard slump cone, measuring 300 mm in height, with a 200 mm diameter at the base and a 100 mm top height, was positioned on a flat, non-absorbent surface. The cone was filled in three layers, each compacted with a 16 mm diameter tamping rod. (Nikmehr et al., n.d.).

Figure 3: Slump Test

Once the top was raised, the cone was raised upwards in 5-10s, letting the concrete slump freely. The value of the slump was determined as the difference between the height of the mold and the slumped concrete within a range of the nearest 5 mm (Khanapur et al., 2025) The test shows the consistency of the concrete and its appropriateness for use in structural works(Alqarni et al., 2022).

2.5.2 Mechanical Strength Test

2.5.2.1 Compressive Strength Test

Compressive strength was determined following ASTM C39/C39M-21 guidelines using a Universal Testing Machine (UTM) with a 2000 kN capacity. Cylindrical specimens were positioned axially and subjected to a steady load rate of 0.25 MPa/s until failure occurred (Alqarni et al., 2022; Tamanna et al., 2024). The compressive strength f_c, was calculated using:

$$f_c = P/A \qquad (1)$$

where P represents the maximum load in newtons (N) and A denotes the cross-sectional area in square millimeters (mm²).

Figure 4: Compressive Strength Test

Every mix type was done using three specimens at 7 days and 28 days of curing. Most failure modes were cone-type and shear, which proved to be good compaction and bonding. The test offered data to compare the strength produced by treated RCA to that of the natural aggregate concrete (Huang et al., 2024; Khanapur et al., 2025).

2.5.2.2 Splitting Tensile Strength Test

The splitting tensile strength test was conducted following ASTM C496/C496M-22 standards, using a 2000 kN Universal Testing Machine (UTM). Cylindrical samples measuring 100 mm × 200 mm were positioned horizontally between steel bearing strips and subjected to a constant load rate of 0.05 MPa/s until they failed (Alqarni et al., 2022). The tensile strength was calculated using:

$$f_t = 2P/\pi DL \qquad (2)$$

where P represents the maximum load (N), D denotes the diameter, and L indicates the length (mm).

Figure 5: Splitting Tensile Strength Test

Three specimens from each mix were tested at 7 and 28 days. The test evaluated the crack resistance and bond strength of treated RCA concrete (Khanapur et al., 2025; Savva et al., 2021).

3.RESULTS & DISCUSSION

3.1 Slump Test

The workability of concrete containing treated recycled aggregates (TRA) was evaluated using the slump test, as specified to ASTM C143/C143M-20. The slump rate declined gradually as the TRA replacement level also rose with different levels of 20, 50, and 80 percent TRA at 90 mm (control), 75 mm, 60 mm, and 50 mm, respectively. This indicates a decrease in fluidity as the recycled agglomeration replacement is at higher levels, which is consistent with the surface roughness and porosity of the aggregates. Nevertheless, this slump lapse, the TRA mixes were demonstrated to have 18-28 percent greater slump compared to untreated recycled aggregate concrete (URA). Thus, it can be concluded that the chemical treatment efficiently suppressed water uptake and enhanced the interfacial transition zone (ITZ) between aggregates and cement paste.

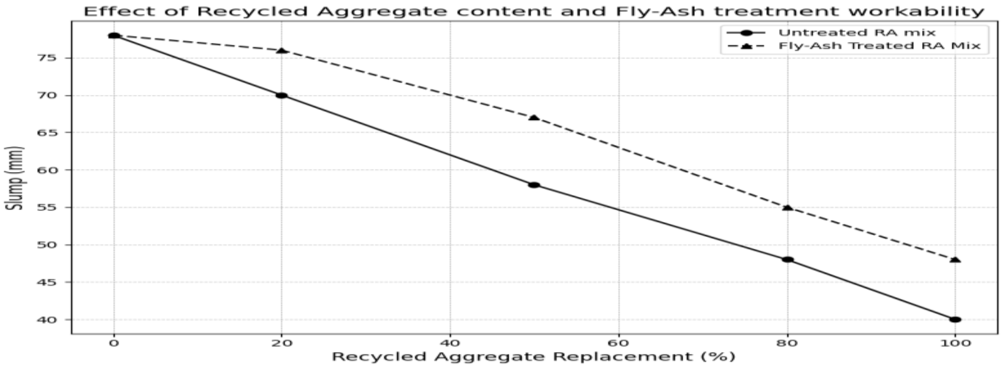

Figure 6: Effect of recycled aggregate replacement and fly-ash treatment on concrete workability.

As Figure 6 demonstrates, the TRA mixes retained workability with higher replacement levels compared to URA mixes, with the values of TRA mix slump being higher at all inclusion levels. The 20-30% replacement of TRA was the most optimum, and the slump was reduced to acceptable limits of structural concrete. At a replacement rate of more than 50 percent, the workability of both treated and untreated mixes declined significantly due to the rougher surface and enhanced porosity of the RCA. This finding is consistent with (Forero et al., 2022), who found an increase in slump of 20-25% after adding acid, and (Alqarni et al., 2022) Who found an increase in slump of 15-35% with the use of sodium-silicate coatings. Also reported that the best workability under local conditions in Bangladesh is 30% RCA replacement (Ismail et al., 2017). These findings demonstrate that surface-treated recycled coarse aggregates (RCA) improve the workability of concrete by reducing internal friction and enhancing cohesiveness, and therefore, they can be successfully incorporated into high-performance and eco-friendly concrete. The treatment of fly ash also enhances its fresh characteristics to ensuring the improved performance of sustainably constructed buildings.

3.2 Compressive Strength Test

The compressive strength of the recycled aggregate concrete (RAC) followed a similar trend at both 7 and 28 days. The control mix (RA 0) yielded the maximum strength of untreated concretes. The compressive strength declined gradually with an increase in the recycled aggregate (RA) content due to adhered mortar, increased porosity, and a weak interfacial transition zone (ITZ) (Alqarni et al., 2022; Forero et al., 2022). Compressive strength was significantly improved in concretes prepared using fly-ash-treated recycled aggregates (TRA) compared to the control, indicating that the adverse impact of porous aggregates on concrete strength was indeed real (Khanapur et al., 2025). The fly-ash coating filled the pores of the surface, refining the aggregate texture. This change improved the bond between the cement paste and aggregate, offering greater stress transfer through the ITZ. The slurry fly ash occupied the microvoids within the aggregate surface. When the fly ash amorphous silica was subjected to hydration, the calcium hydroxide reacted with amorphous silica to produce secondary calcium-silicate-hydrate (C-S-H) gel. This response tightened the microstructure, enhanced cohesion and decreased internal porosity (Balasubramani & Palaniappan, 2025; Huang et al., 2024).

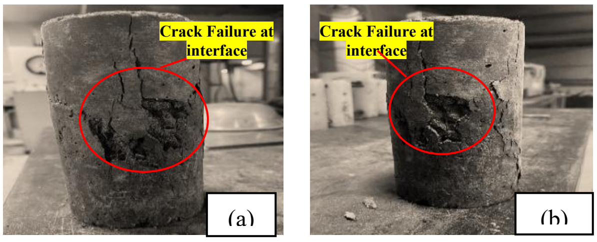

Figure 7:(a) Cone-type fracture and (b) Shear-type fracture

In Figure 7, cone-type fractures occur due to brittle failure due to internal stress, and shear-type fractures occur due to shear stress due to diagonal cracks. TRA mixes had fewer fractures of shear type, so fly ash treatment increased the strength and decreased the brittle failure by enhancing the interfacial transition zone (ITZ) of untreated recycled aggregate concrete (URA).

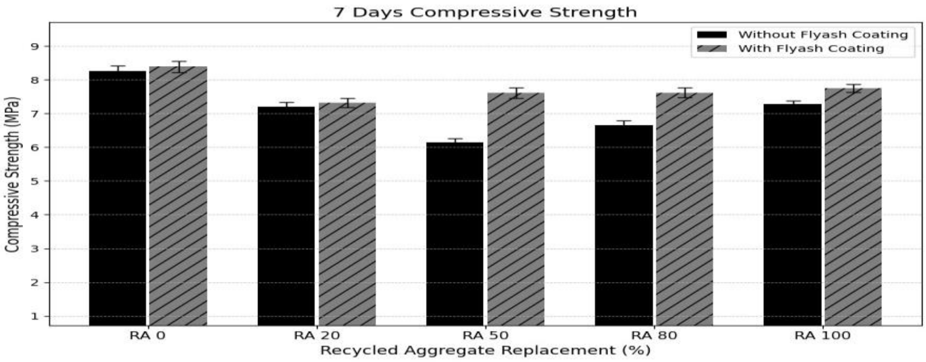

Figure 8: Early-age (7-day) compressive strength of untreated and fly-ash-coated RAC.

Figure 8: 7-day compressive strength indicates that there has been a considerable enhancement in the strength of concrete with the use of fly-ash-coated recycled aggregates (TRA) over the normalized recycled aggregate concrete (URA). The control mix (RA0) exhibited the best compressive strength, and TRA mixes were consistently more effective than URA mixes. In the case of RA0, TRA was 8.39 MPa as opposed to 8.26 MPa in untreated concrete. The TRA mixes remained stronger with an increase in the RA content; for example, at a 50 percent replacement of RA, the TRA was 7.61 MPa, whereas the URA was 6.14 MPa. TRA mix at 100% RA was 7.28 MPa, exceeding URA at 7.2 MPa. This can be attributed to the fact that the strengthening is a result of fly ash treatment, which minimizes water absorption, enhances adhesion between the cement paste and aggregate, and enriches the interfacial transition zone (ITZ), leading to improved early hydration and packing within the cement matrix.

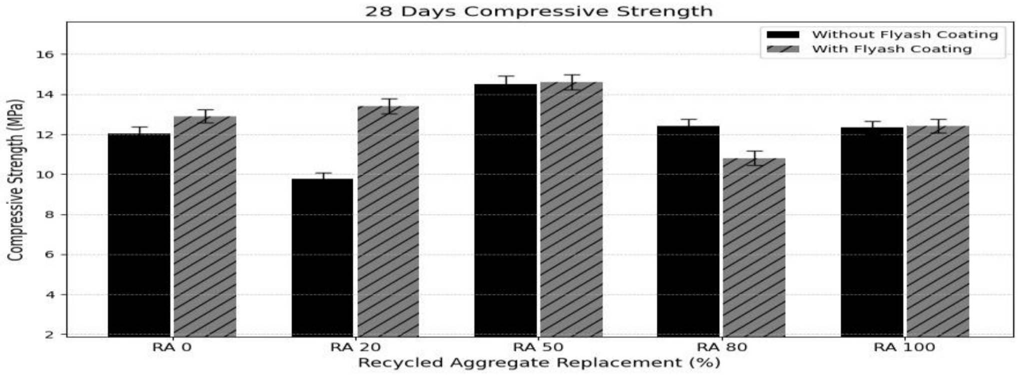

Figure 9: 28-day compressive strength development of RAC with varying RA content.

TRA mixes remained ahead of URA mixes at 28 days (see Figure 9). The RA 50 mix, containing 50% TRA, reached a compressive strength of 14.6 MPa, surpassing the natural-aggregate control at 12.9 MPa. This improvement is due to the pozzolanic reaction of fly ash, where amorphous silica reacts with calcium hydroxide to form additional calcium-silicate-hydrate (C-S-H) gel, increasing the density of the microstructure and the transition zone. This reaction strengthens the bond between aggregate and cement paste, improving stress transfer and crack resistance. For the RA 100 mix, the TRA was 12.3 MPa, higher than the untreated mix at 12.0 MPa but lower than the RA 50 mix. This result aligns with (Huang et al., 2024) who also observed that the strength improves with fly-ash treatment, especially at moderate RA replacement levels of 20-50%.

3.3 Tensile Strength Test

The tensile strength of fly ash-treated recycled aggregate concrete (RAC) increased significantly at 7 and 28 days compared with untreated mixes. Fly ash treatment improved the interfacial transition zone (ITZ) and reduced water absorption, thereby enhancing the bond between aggregates and cement paste and increasing tensile performance. The treatment is effective in overcoming the deficiencies of recycled aggregates, i.e., porosity and micro-cracked adhered mortar, which generally reduces the tensile strength of untreated RAC (Kazemian et al., 2019).

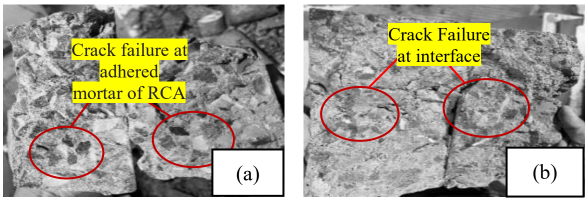

Figure 10: (a) crack through adhered mortar and (b) crack at aggregate paste interface.

Figure 10 displays normal failure modes that occur during the tensile strength test. Figure 10(a) shows a fracture that has been caused by cement paste adhering to the mortar, and this is more prevalent in untreated mixes, as there is poor adhesion between the cement paste and the aggregates. The cracks at the aggregate-paste interface, as shown in Figure 10(b), are less common in fly-ash-treated RAC due to enhanced bonding and a thicker ITZ, which supports the notion that fly-ash treatment enhances the tensile strength of recycled aggregate concrete.

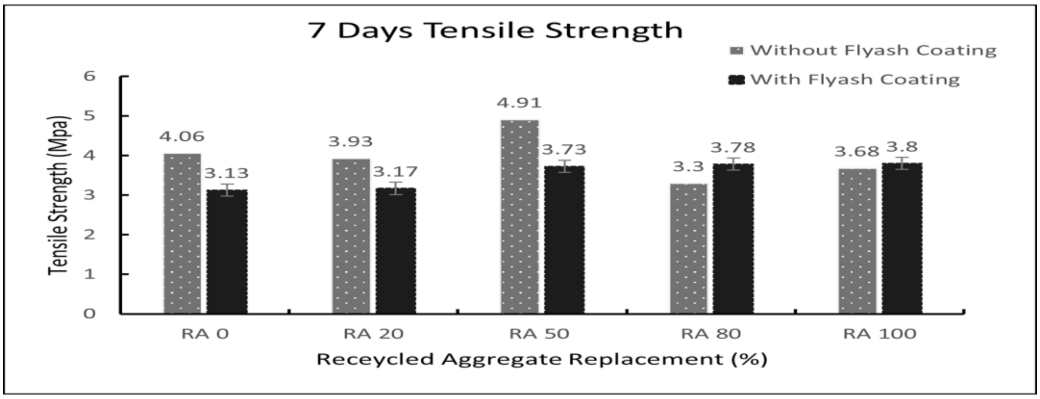

Figure 11: Early-age (7-day) tensile strength of untreated and coated RAC mixes

At 7 days, the tensile strength of untreated RAC declined gradually from 4.06 MPa (RA 0) to 3.13 MPa (RA 100), reflecting a drop caused by the weak ITZ and the high porosity of the recycled aggregates. (Kazemian et al., 2019). Fly-ash-treated mixes showed significant improvements at every replacement level. RA 20 increased from 3.93 MPa to 4.91 MPa, and RA 50 and RA 80 improved their tensile strength by approximately 10-15 percent. Even RA 100 reached 3.8 MPa, compared with 3.3 MPa in untreated mixes. The fly ash treatment filled the surface, creating a denser ITZ that inhibited crack initiation and increased early-stage tensile strength. (Huang et al., 2024; Khanapur et al., 2025).

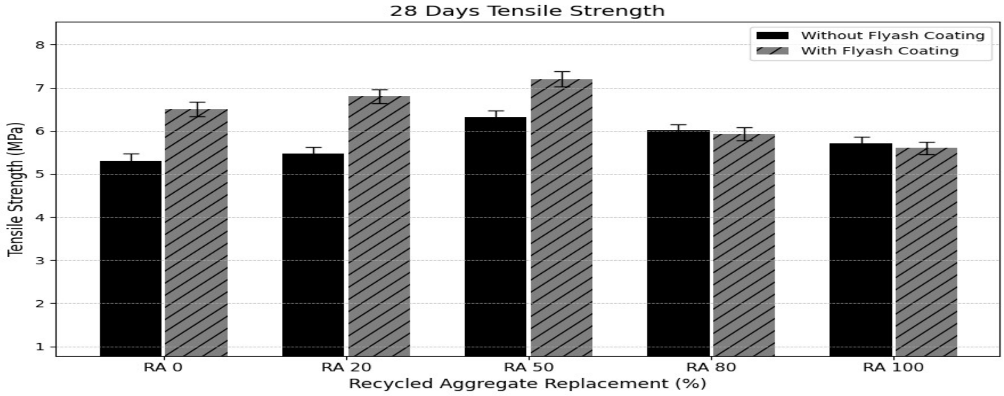

Figure 12: 28-day tensile strength evolution of RAC incorporating fly-ash-coated aggregates.

The tensile strength of fly ash-treated recycled aggregate concrete (RAC) at 28 days also increased compared to untreated mixes. Figure 12 illustrates that the untreated RAC exhibited a tensile strength ranging from 6.51 MPa (RA 0) to 5.3 MPa (RA 100). This was not the case in fly-ash-treated mixes, with RA 20 attaining highs of 6.8 MPa, RA 50 attaining 7.2 MPa, and RA 100 attaining 5.6 MPa. The pozzolanic reaction of fly ash, which occurs to create secondary calcium-silicate-hydrate (C-S-H) gel, can explain the 30% increment in tensile strength over untreated mixes. The reaction makes the interfacial transition zone (ITZ) dense and increases crack-bridging capacity (Kępniak et al., 2025). The more dense ITZ enabled providing more stress between the former mortar and the new paste, which correlates with the results of (Ahmed et al., 2021; Korjakins et al., 2024). The tensile strength increase between 7 and 28 days was 75 percent for treated mixes, and 55 percent for untreated mixes, indicating that microstructural densification occurred more rapidly in the treated concretes.

Finally, fly-ash treatment significantly increases the tensile strength of recycled aggregate concrete (RAC), particularly when the ratio between RA and TRA is 50. TRA mixes consistently performed better compared to untreated mixes. Mechanical scrubbing, acid washing, and fly-ash coating enhance the ITZ, decrease the porosity, and increase stress transfer between the cement paste and aggregates. TRA was found to mix with RA replacement at 20-50%, indicating improved tensile properties and transforming RAC into a non-porous, cohesive composite with enhanced crack resistance. These results demonstrate that fly ash treatment is an efficient procedure for increasing the mechanical characteristics of recycled aggregate concrete as a sustainable construction.

3.4 Future Work

Future studies should focus on the long-term durability of fly ash-treated recycled aggregate concrete (RAC), particularly in harsh environments, such as those exposed to freeze-thaw cycles and chloride intrusion. More in-depth microstructural analyses using SEM and XRD should be conducted to characterize the interfacial transition zone (ITZ). Additionally, varying the fly ash dosage and exploring different types of fly ash would help enhance both early-age and long-term behavior. To perform a more extensive assessment of the sustainability of treated RAC, life-cycle assessments (LCA) and carbon footprint analysis should also be included.

4.CONCLUSION

This paper highlights the significant improvements in the mechanical properties of recycled aggregate concrete (RAC) when fly ash is incorporated. At a maximum replacement rate of 50% of the recycled aggregate, the treated RAC achieves compressive strengths of up to 14.6 MPa and tensile strengths of up to 7.2 MPa. The mechanical scrubbing, acid washing, and fly ash coating form a synergistic combination that enhances the interfacial transition zone (ITZ), resulting in improved stress transfer, increased crack resistance, and overall strength. Additionally, fly ash treatment leads to a 25% decrease in water absorption and an impressive 18-28% increase in workability. These results confirm that fly-ash-treated RAC is a sustainable, high-performance alternative to traditional concrete, which creates an eco-effective solution to decrease the reliance on natural aggregates and promotes the principles of the circular economy. The approach can significantly reduce the environmental impact by promoting low-carbon construction methods and ensuring sufficient structural integrity to support various uses. Finally, fly-ash-treated RAC could be regarded as one of the innovative solutions to sustainable concrete production, as it guarantees high performance and environmental sustainability.

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DECLARATION OF USE OF AI

The authors declare that they used artificial intelligence (AI) tools to assist in preparing this manuscript. All content was reviewed and approved by the authors, who assume full responsibility for the accuracy and completeness of the final version. The AI tool did not produce any original scientific results or conclusions.

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