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Research Article

Sustainable geopolymer concrete for pavements: Performance evaluation of recycled concrete aggregates in fly ash-based mixtures

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ABSTRACT

This study investigates the feasibility of incorporating recycled concrete aggregates (RCA) into fly ash-based geopolymer concrete for sustainable pavement applications. The research evaluates RCA's physical and mechanical properties compared to virgin coarse aggregates (VCA) and assesses the performance of geopolymer concrete mixtures with up to 40% RCA replacement. Aggregate characterization revealed that RCA exhibited higher water absorption (4.39%), crushing value (20.9%), impact value (28.2%), and abrasion value (26.1%) compared to VCA, yet these values remained within acceptable limits for pavement applications. Geopolymer concrete specimens were tested for compressive strength, water absorption, abrasion resistance, and chloride ion permeability. Results indicated that increasing RCA content led to a gradual decrease in compressive strength, from 40.16 MPa to 33.52 MPa, while water absorption increased from 5.2% to 6.8%. Abrasion resistance declined as RCA content rose, and chloride ion penetrability increased from 1687 to 2196 coulombs. However, mixtures with up to 20% RCA replacement met the strength and durability criteria required for pavement construction. This study demonstrates the potential for utilizing RCA in geopolymer concrete pavements, offering a sustainable solution for waste management and resource conservation in the construction industry.

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1. INTRODUCTION

Using recycled concrete aggregates (RCA) in pavement construction has emerged as a crucial strategy to address the growing environmental concerns and resource scarcity in the construction industry [1]. With global concrete production exceeding 10 billion tons annually, construction and demolition waste poses significant ecological challenges [2, 3]. Simultaneously, the depletion of natural aggregate resources has become a pressing issue in many regions [4]. In this context, incorporating RCA in pavement construction offers a sustainable solution that addresses waste management and resource conservation [5]. The use of RCA in pavements also aligns with circular economy principles, reducing the carbon footprint associated with aggregate production and transportation [6]. Tam et al. [7] estimated that incorporating RCA in pavement construction could reduce CO_2 emissions by up to 20% compared to conventional methods.

On the other hand, Geopolymer concrete has emerged as a promising alternative to traditional Portland cement concrete in pavement construction, offering significant environmental and performance benefits [8, 9]. This innovative

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Table 1. Physical and chemical characteristics of binders

	SiO_2	CaO	Al_2O_3	Fe_2O_3	Na_2O	MgO	SO_3	LOI	Specific gravity	Specific surface area (m^2/g)
Fly ash	58.32	4.08	25.71	5.27	0.37	1.04	0.92	4.29	2.39	5.12
GGBFS	34.16	44.25	12.23	1.02	0.78	3.61	0.73	3.22	2.86	6

material, which utilizes industrial by-products such as fly ash or ground granulated blast furnace slag as binders activated by alkaline solutions, can reduce CO_2 emissions by up to 80% compared to ordinary Portland cement concrete [10]. Geopolymer concrete exhibits superior durability, including enhanced resistance to chemical attack, freeze-thaw cycles, and chloride ion penetration, critical factors in pavement longevity [11]. It also offers rapid strength gain, allowing for faster construction and earlier traffic opening, and demonstrates better performance under extreme temperature conditions.

Geopolymer concrete has the combined advantages of a lower carbon footprint binder system based on industrial waste fly ash, with an opportunity to incorporate another waste stream as aggregate [12]. Work on RCA recycled into non-geopolymer concrete shows that at high replacement levels, RCA affects concrete properties such as lower density, higher water absorption, lower mechanical strength, more significant shrinkage, and lower durability compared to natural aggregates (NA) [13]. In terms of compressive strength, de Juan and Gutiérrez [14] observed up to 5–30% lower strength when replacing NA with 25–100% coarse RCA due to RCA's higher porosity and water absorption. Other studies [15, 16] have also found the rate of strength gain of RCA concrete to be slower than that of NA concrete. Research indicates substitution limits of 20–30% coarse RCA are suitable for structural concrete applications [17].

Regarding durability, Pepe et al. [18] reported that up to 100% replacement of NA by coarse or fine RCA had negligible effects on freeze-thaw resistance. Corrosion resistivity was also similar, with up to 30% replacement levels [19]. Permeability and diffusion testing showed higher chloride ingress rates with higher RCA replacement ratios [20]. Drying shrinkage strains were found to be 10–25% higher with RCA incorporation [21].

In particular, geopolymer concrete derived from industrial by-products, serving as a sustainable construction material alternative to traditional Portland cement concrete, has not undergone substantial investigations evaluating the incorporation of RCAs. Additionally, earlier RCA research is predominantly limited to the impacts on compressive strength and essential durability characteristics like sorptivity and acid/sulfate resistances. Evaluating longevity indicators such as volumetric abrasion loss and rapid chloride permeability, which better quantify actual concrete pavement performance, can support extending RCAs to road infrastructure where durability against water/chloride ingress is vital. Therefore, a research gap exists in applying learnings from RCA use in standard concrete to geopolymer concrete for structural applications. This study assesses the effects of coarse RCA content on the core mechanical strength and various relevant durability metrics of fly ash-based geopolymer. Outcomes can support preliminary standardization for greener concretes using waste and by-product-sourced materials. With this research gap in mind, this study evaluates the use of crushed recycled concrete aggregates (RCA) to replace natural coarse aggregates in fly ash-based geopolymer concrete partially. The research experimentally evaluates geopolymer concrete incorporating up to 40% replacement of natural coarse aggregate with RCA. Strength, abrasion resistance, water absorption, and chloride permeability are tested to gauge detrimental effects. This study aims to establish a framework for utilizing waste concrete in next-generation sustainable pavements, addressing environmental concerns and structural performance needs by determining optimal RCA replacement levels that maintain required engineering properties.

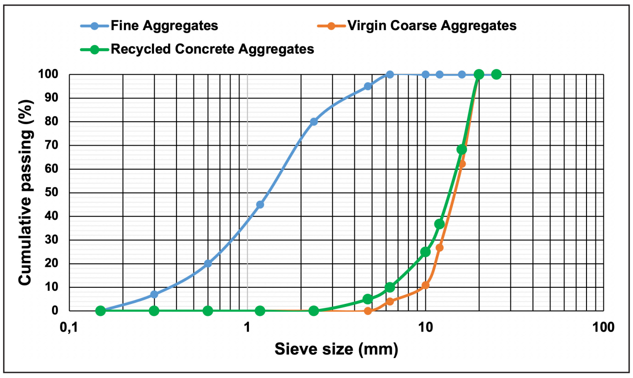

Figure 1. Particle size distribution of aggregates.

2. MATERIALS AND METHODS

2.1. Materials

In the present study, Fly ash (FA) and ground granulated blast furnace slag (GGBFS) were used as geopolymer binders, conforming to ASTM C618-08 [22] and ASTM C989-18 [23] respectively (Table 1). FA was sourced from a local coal-fired thermal power plant, while GGBFS was obtained commercially (JSW Cements Ltd., India). Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were used as alkaline activators, procured from local chemical suppliers. The Na_2SiO_3 had a composition by weight of Na_2O 14.5%, SiO_2 29.6% and water 55.9%. Locally sourced granite stone and river sand provided the coarse and fine aggregates conforming to ASTM C33 [24] and BS 882 grading requirements [25]. The coarse aggregate was sieved into 20 mm and 12 mm fractions while the fine aggregate passed through a 4.75 mm sieve, as shown in Figure 1. A NaOH: Na_2SiO_3 ratio of 1:2.5 was used for

Table 2. Mix Calculations (kg/m³)

Mix	FA	GGBFS	Aggregates			NaoH	Na_2SiO_3	S/B
			Fine	VCA	RCA			
RA0	336	84	570	1140	–	108.57	43.43	0.40
RA10	336	84	570	1026	114	108.57	43.43	0.40
RA20	336	84	570	912	228	108.57	43.43	0.40
RA30	336	84	570	798	342	108.57	43.43	0.40
RA40	336	84	570	684	456	108.57	43.43	0.40

the alkaline activator based on previous work [12, 26]. The 8M NaOH solution was prepared 24 hrs before mixing and cooled in an ice bath [2], and its preparation process is shown in Figure 2.

2.2. Preparation of Recycled Aggregates

Recycled concrete aggregates (RCA) were produced from previously tested concrete samples in our laboratory. The process involved crushing the concrete samples using a laboratory jaw crusher and washing them to remove dust and fine particles. The washed aggregates were oven-dried at 105 °C for 24 hours [27, 28]. Finally, the dried aggregates were sieved to match the grading of the natural aggregates used in this study. The present study did not follow a specific standard for this process, and this method is similar to those described in ASTM C33 [24] and BS EN 12620 [29] for processing recycled aggregates.

2.3. Mix Design and Curing

Geopolymer concrete mixes were designed as per IS 10262-2019 (Table 2) [30–32], with RCA replacing 0%, 10%, 20%, 30%, and 40% of the coarse aggregate by volume. Additionally, 20% of GGBFs was used to replace the fly ash in all mixes. Dry components were pre-mixed for 2–3 minutes before adding the alkaline activator and mixing for 5–6 minutes. The geopolymer concrete specimens were cured under ambient conditions for 28 days. In this investigation, 160 specimens (i.e., 80 cubes for compressive strength and water absorption, 40 cylinders for the abrasion resistance test, and 40 disc specimens for the rapid chloride permeability test) were prepared and tested throughout the experimentation.

2.4. Experimental Methods

2.4.1. Aggregate Tests

The aggregate impact test was carried out as per IS 2386 Part 4 [33]. The aggregate sample was first oven-dried at 100 °C to 110 °C and allowed to cool. It was then filled in the cylindrical steel cup of the impact testing machine to overflow and was tamped 25 times with a tamping rod. The weight (W1) of aggregates was determined before subjecting the cup fixed in position to 15 blows of hammer rotated from a height of 380 mm. The crushed aggregate was removed and sieved through a 2.36 mm IS sieve. The fraction passing the 2.36 mm sieve (W2) was weighed, and the aggregate impact value was calculated using Eq.1.

Aggregate impact value (%)=((W1–W2)/W1)x100 Eq.1

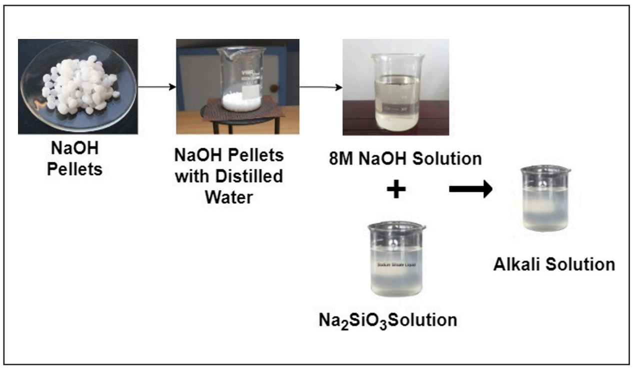

Figure 2. Geopolymer solution preparation [2].

The aggregate crushing strength test was performed per IS 2386 Part 4 [33]. The oven-dried aggregate sample was sieved through 12.5 mm and 10 mm IS sieves. Aggregates passing a 12.5 mm sieve and retained on a 10 mm sieve were selected. Three test specimens were prepared by mixing aggregates of different sizes to get an aggregate weight of approximately 100 g in each case. The specimens were placed in compression testing machines one by one, and load was applied at a uniform rate of 40 tonnes/minute until failure occurred. The crushing load for all three specimens was noted, and their average was taken as the aggregate crushing strength.

The abrasion test was carried out as per IS 2386 Part 4 [33]. The coarse aggregate sample was oven-dried and then divided into 6 equal parts, mixing them thoroughly. The one-part sample was taken and was sieved through a 1.7 mm IS sieve. The fraction passing was discarded. The retained sample was placed in an abrasion testing machine cylinder in 5 layers, tamping each layer 25 times. The sample was then subjected to 100 revolutions in an abrasion testing machine. After that, the abraded aggregate was sieved through a 1.7 mm IS sieve, and the fraction passing through the sieve was weighed. The percentage of wear due to abrasion was then calculated.

As per IS 2386 Part 3 [34], the water absorption test was performed by oven drying the aggregates to constant mass first. The dried aggregates were then immersed in water for 24 hours, taken out, wiped to remove traces of water, and weighed (W1). The aggregates were again submerged in water for 72 hours, removed, surface wiped, and weighed (W2). The water absorption was calculated using the Eq.2.

Water absorption (%)=((W2–W1)/W1)x100 Eq.2

Figure 3. Compressive strength setup.

2.4.2. Compressive Strength

The concrete compressive strength test was carried out as per IS 516 [35–38] by casting three 150mm concrete cubes, demolding after 24 hours, curing by immersion in water for 28 days, wiping the cubes dry, placing them in compression testing machine one by one, aligning blocks properly, and applying load uniformly at a rate of approximately 140 kg/sq cm per minute until failure occurred. The maximum load divided by the cross-sectional area gave the compressive strength. Figure 3 shows the experimental setup of the compressive strength.

2.4.3. Abrasion Resistance Test

The abrasion resistance test was performed as per IS 1237 [39] by casting concrete into 140 mm diameter and 60mm height cylinders in steel molds, demolding after 24 hours, curing by immersion in water for 28 days, and then oven drying. The specimens were set up in the abrasion testing machine wearing a test rig rotated at 30–33 rpm and subjected to abrasive action of 200 revolutions wearing a path of 52mm length uniformly before weighing percentage wear. The abrasion resistance was calculated using the Eq.3.

Abrasion resistance = ((Initial weight-Final weight)/Initial weight)x100 Eq.3

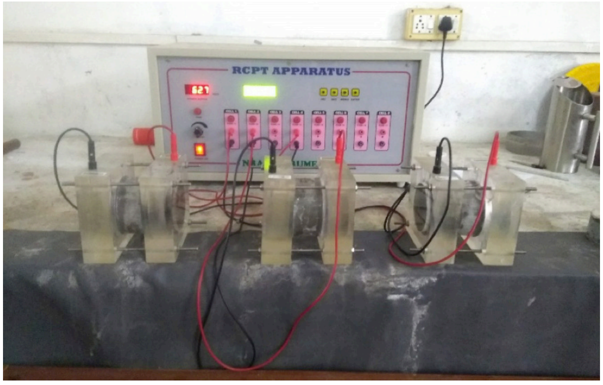

Figure 4. Rapid chloride permeability test setup.

Figure 5. Water absorption test setup.

Where;

Initial weight = Weight of specimen before the test; Final weight = Weight of specimen after the test.

2.4.4. Rapid Chloride Permeability Test

The rapid chloride permeability test was conducted as per ASTM C1202 [40–43] by casting 100mm diameter and 50mm height concrete specimens, demolding after 24 hours, and curing by immersion in water for 28 days. The test apparatus containing the vacuum-saturated specimen was connected to a 60V DC source for 6 hours, during which the passed electrical charge was monitored periodically before calculating chloride permeability. Figure 4 shows the experimental photograph of the Rapid chloride permeability test setup.

2.4.5. Water Absorption

The water absorption test was performed as per IS 1199 [44–47] by casting concrete cubes of 150mm size, demolding after 24 hours, and curing by immersion in water for 28 days. The cured specimens were dried in an oven at 100–105 °C to constant mass. After cooling, the cubes were immersed in water for 72±2 hours. The specimens were then weighed in water and after surface drying to determine water absorption using the percentage increase in mass. Figure 5 shows the experimental setup of the water absorption test.

Table 3. Physical and mechanical properties of Virgin and Recycled aggregates

	Specific gravity	Density (kg/m³)	Water absorption (%)	Aggregate crushing value (%)	Aggregate impact value (%)	Abrasion value (%)
VCA	2.64	1542	1.75	17.2	16.78	14.3
RCA	2.51	1366	4.39	20.9	28.2	26.1
IS 2386 Limits for pavements	2.5–3.0	1500–1700	<2%	<30%	<30%	<30%

3. RESULTS AND DISCUSSION

3.1. Physical and Mechanical Properties of Recycled Coarse Aggregates

Table 3 presents the physical and mechanical properties of Virgin Coarse Aggregates (VCA) and Recycled Concrete Aggregates (RCA) in comparison with the IS 2386 limits for pavements. The results reveal notable differences between VCA and RCA across all measured parameters. The specific gravity of RCA (2.51) is lower than that of VCA (2.64), consistent with the previous studies. This reduction aligns with findings by Verian et al. [48], who reported specific gravity values for RCA ranging from 2.35 to 2.58. The lower specific gravity of RCA can be attributed to the presence of adhered mortar, which is less dense than the original aggregate (McNeil and Kang, 2013) [49]. The density of RCA (1366 kg/m³) is substantially lower than VCA (1542 kg/m³), further confirming the increased porosity. While the VCA density falls within the IS 2386 limits for pavements (1500–1700 kg/m³), the RCA density is slightly below this range, which may require consideration in mix design for pavement applications.

The RCA exhibits significantly higher water absorption (4.39%) compared to VCA (1.75%), exceeding the IS 2386 limit of <2% for pavements. This increased absorption is consistent with studies by Saravanakumar et al. [50], who reported water absorption values for RCA between 4.5% and 7.0%. The higher absorption is primarily due to the porous nature of the adhered mortar in RCA. This characteristic can lead to workability issues in fresh concrete and potential long-term durability concerns in hardened concrete. To mitigate these effects, special consideration may be needed in mix design, potentially including using water-reducing admixtures or pre-saturation techniques for RCA (Verian et al. [48]).

Aggregation impact and crushing tests determine the Resistance against externally applied loads. Impact value signifies the ability to resist sudden shocks while crushing value indicates the capacity to sustain gradual compressive loads without excessive breakdown. Owing to the attached porous old mortar phase on RCA particles, both impact and crushing values are higher than VCA. Both the crushing value (20.9%) and impact value (28.2%) of RCA are higher than those of VCA (17.2% and 16.78%, respectively). These results align with findings by Wang et al. (2017) [51], who observed crushing values for RCA between 24% and 35%. The increased crushing and impact values indicate lower resistance to mechanical stresses, which can be attributed to the weaker adhered mortar and potential micro-cracks in RCA resulting from the crushing process (Xiao et al., [52]). All values are within the IS 2386 limit (<30%), suggesting better quality RCA than previous studies.

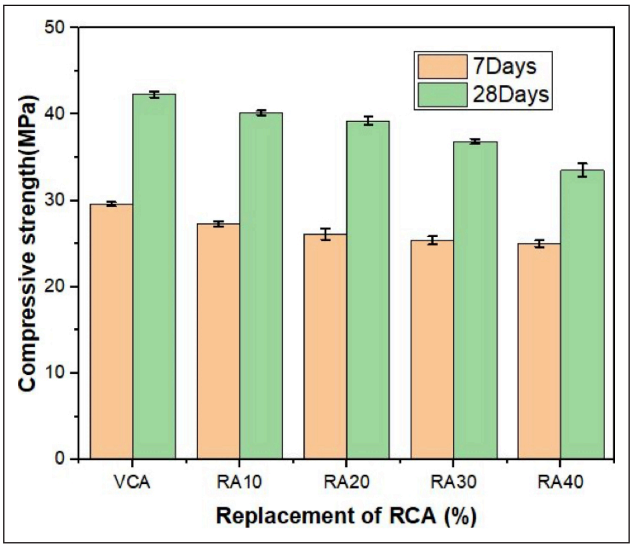

Figure 6. Compressive strength of RCA-based geopolymer concrete.

The abrasion value empirically quantifies wear and tear from rubbing/grinding actions through standard attrition test methods. Abrasion induces progressive particle disintegration, influencing concrete structures' long-term strength and stability. The RCA demonstrates a higher abrasion value (26.1%) compared to the VCA (14.3%), but both are within the IS 2386 limit of <30%. This aligns with the work by Silva et al. [53], who reported abrasion values for RCA ranging from 30% to 44%. The current results show lower abrasion values for both VCA and RCA than the previous studies, indicating better wear resistance.

These new results suggest that the RCA used in this study is of higher quality than the previous studies, with improved mechanical properties. This could lead to better performance in pavement applications. However, the higher water absorption and slightly lower mechanical strength of RCA compared to VCA may still necessitate adjustments in mix design, potentially including the use of supplementary cementitious materials or chemical admixtures to mitigate adverse effects on workability and long-term durability (Verian et al., [48]), with this concern these aggregates were partially replaced in the Virgin Coarse Aggregates used in geopolymer concrete for the pavement applications.

3.2. Compressive Strength

Figure 6 outlines the 28-day compressive strength exhibited by geopolymer concrete containing varying replacement percentages of natural aggregates via recycled concrete aggregates (RCA). Assessment of strength de-

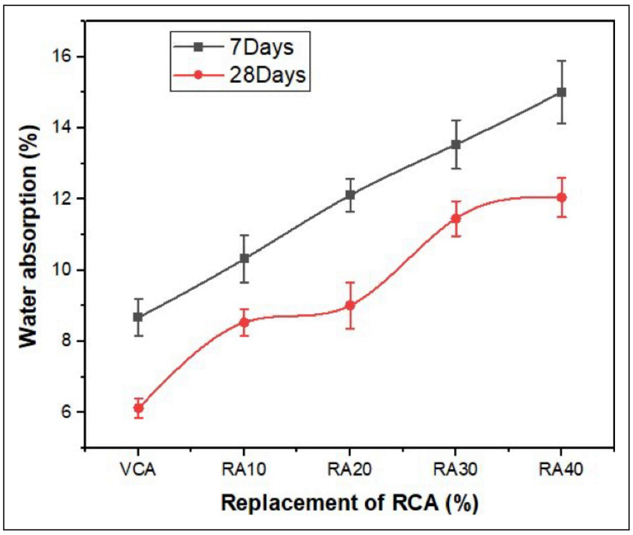

Figure 7. Water absorption of RCA-based Geopolymer concrete.

velopment is imperative to determine the feasibility of achieving standard structural requirements when utilizing recycled aggregate mixes. It is evident that progressively increasing the RCA percentage as a substitute for virgin coarse aggregates results in the gradual decline of compressive strength in the hardened geopolymer concrete from 40.16MPa to 33.52MPa. However, the concrete mixes with 10% and 20% RCA comfortably satisfy the target mean strength of 35MPa at 28 days for M35 grade concrete intended for pavement applications.

The noticeable drop in strength ensues due to the inherent disparity between natural aggregates' properties and recycled aggregates discussed earlier. The porous, weak zones emerging from old adhered mortar on RCA particles generate discontinuities in what would be a monolithic microstructure with only VCA [54]. Moreover, the higher water absorption capacity interferes with efficient particle packing, increasing the voids ratio. Both phenomena provoke more significant defect sites in the hardened concrete composite, allowing failure under loading to initiate and propagate through weaker zones across the RCA interfacial pockets [55]. Additionally, rapid strength development associated with pure geopolymer systems gets marginally deferred in the presence of RCA, where the aggregates possess lower strength characteristics that translate to the bulk matrix. However, over extended periods, the geopolymerization process aids strength gain by forming stable three-dimensional binder structures enveloping the aggregates [56]. Compatibility between the geopolymer gel and RCA improves with curing, mitigating the negative trends seen during the early stages. The nature of the bulk paste-aggregate interface impacts load transfer efficiency and measured strength performance. Hence, the CA percentage must be restricted, and suitable admixtures must be adopted to boost interfacial bonding, densification, and longer-term strength development to attain reliable structural quality geopolymer concrete containing recycled aggregates.

3.3. Water Absorption

Figure 7 represents the water absorption exhibited by geopolymer concrete mixes containing increasing percentages of recycled concrete aggregates (RCA) as replacements for natural aggregates after 28 days of curing. Evaluating sorptivity behavior is necessary to ensure the permeation properties are not adversely altered in RCA-based concrete, which can undermine durability against environmental exposure during service life. The results show that as the RCA replacement ratio is enhanced incrementally from 0% to 40%, the water absorption values of the geopolymer concrete increase gradually from 5.2% to 6.8%. However, all the mixes demonstrate water absorption within the specified limit of 7% for structural concrete applications. The visible escalating trend is anticipated and is attributed primarily to the higher individual absorption capacity of the recycled aggregates arising from the porous adhered old mortar on particles that retain additional moisture [57].

When recycled aggregates are integrated into the concrete matrix, the networks of existing fine pores in the weaker RCA phase translate into the hardened cement paste, producing increased microstructural voids. Moreover, the interfacial transition zone (ITZ) between RCA particles and geopolymer paste tends to weaken, allowing localized penetrability [56]. During mixing, higher absorption by RCA reduces free moisture that can interfere with effective dispersion and encourage flocculation. These factors collectively provoke an escalation in sorptivity [58]. However, specific self-sealing mechanisms emerge over longer-term curing periods as geopolymeric gels diffuse into available pores within RCA, achieving densification.

Moreover, enhanced moisture gets nullified in many practical exposure conditions through drying/evaporation effects preventing saturation except in situations of continuous water contact [59]. Proper air entrainment measures further offset risks from higher absorption capacity. Hence, with a restricted RCA percentage to balance absorption effects, structural stability and durability performance against water penetration remain within the permissible range for RCA-based concretes implied by the test data. However, conservative limits are necessary for universal standardization, warranting significant focus on appropriate curing to control water ingress risks in RCA-integrated concretes.

3.4. Abrasion Resistance of RCA-Based Geopolymer Concrete

Figure 8 represents abrasion resistance evaluated through weight loss in geopolymer concrete mixes incorporating increasing replacement percentages of natural aggregates via recycled concrete aggregates (RCA) after 28 days of standard curing. Determining abrasion behavior is vital to assure surface integrity against progressive material disintegration from friction/impact damage during the service life of concrete structures like pavements. The test results demonstrate that when the RCA content is elevated, the abrasion resistance characterized by the density of concrete lost from the specimen surface declines gradually. The reference mix without RCA exhibits the lowest volume removal of 10.82 cm^3/50

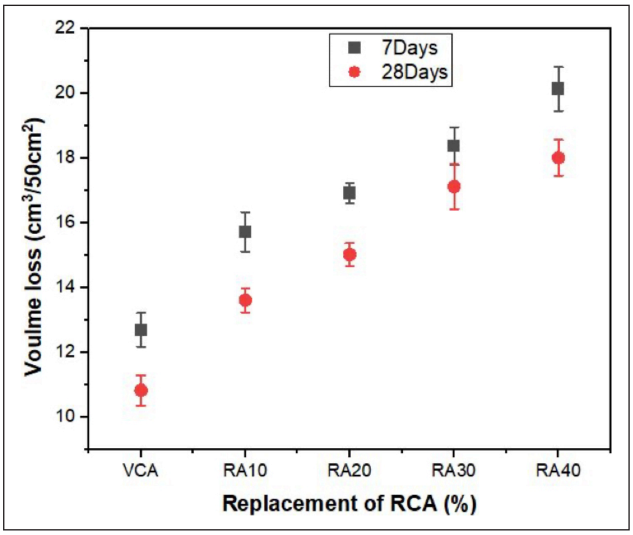

Figure 8. Abrasion resistance of RCA-based Geopolymer concrete.

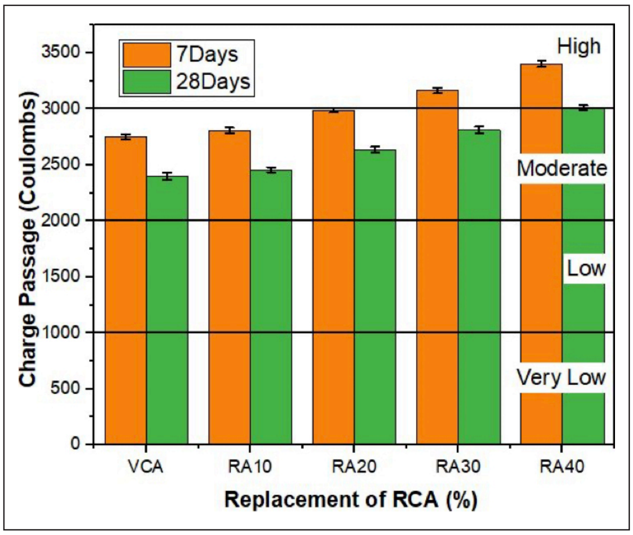

Figure 9. Chloride ions passage of RCA-based Geopolymer concrete.

cm^2, aligning with high-strength performance concretes. As RCA substitution is enhanced to 40%, the abrasion value rises to 18.01 $cm^3/50\ cm^2$, implying that surface integrity becomes more vulnerable to wearing mechanisms but is still within limits for concrete pavement application.

A noticeable reduction in abrasion resistance ensues because the recycled concrete aggregates themselves display inferior surface hardness compared to natural gravels, resulting from the porous, weak zones emerging from old adhered mortar on particles [48, 50]. When loads are applied, these softer sites become prominent locations for crack initiation, which exponentially leads to material failure and breakdown [60]. Moreover, due to higher porosity, the interfacial bonding between RCA particles and geopolymeric paste remains poor, allowing dislodgement of particles under abrasion and exacerbating weight loss [50, 60]. However, upon prolonged moist curing, the geopolymer concrete matrix develops enhanced consolidation as the gel permeates into available voids through the pozzolanic effect, diminishing flaws otherwise present around RCA zones [61]. However, the individual lower hardness characteristics translate proportionally into bulk concrete composite behavior depending on the replacement ratio. Structured optimization of RCA percentage coupled with incorporating abrasion-resistant admixtures like silicon carbide can aid in attaining strength, and abrasion attributes service life for geopolymer concrete containing recycled aggregates.

3.5. Chloride Ion Permeability of RCA-Based Geopolymer Concrete

Figure 9 represents the resistance to chloride ion penetration assessed through total charge passed during accelerated migration testing in geopolymer concrete specimens with up to 40% coarse aggregates replaced via recycled concrete aggregates (RCA). Analyzing chloride diffusivity is imperative to evaluate durability against the ingress of harmful salts, which can initiate rebar corrosion in structurally reinforced concrete. It is discernible that charge passed, which serves as an index of chloride penetrability, rises progressively with an increase in RCA replacement levels from 1687 coulombs for reference mix to 2196 coulombs for 40% RCA mix after 28 days of standard moist curing. However, as per ASTM 1202 classification, all four concrete variations demonstrate low chloride ion permeability, implying appreciable resistance against chloride ingress and corresponding corrosion risks.

The noticeable rise in chloride diffusivity is anticipated. It is a consequence of the relatively more porous and permeable microstructure introduced by the recycled aggregates having weaker interfacial bonding with the geopolymeric paste, which acts as transport paths aiding the migration of chlorides [62]. Moreover, RCA's higher moisture absorption capacity leads to more excellent solution saturation, causing increased chloride transportation compared to only natural aggregates. Nonetheless, over longer durations, densification occurs through secondary geopolymerization infilling pores within the composite transition zones, resulting in the refinement of permeability [63]. Adding mineral admixtures like Metakaolin or GGBFS optimizes packing, leading to narrowed pores that restrain fluid transport. Finer RCA fractions also demonstrate superior chloride resistance than coarser particles, mitigating the negative impacts. Overall, with controlled RCA proportions, geopolymer concretes can achieve adequacy in permeability properties for assured durability, as the test data indicates. Optimization of mix design coupled with modified curing can address the implications of marginally elevated chloride penetrability in sustainable concretes containing recycled concrete aggregates.

4. CONCLUSIONS

Based on the results presented in the attachment, here are specific conclusions for this study:

- Recycled concrete aggregates (RCA) exhibited inferior properties compared to virgin coarse aggregates (VCA), with higher water absorption (4.39% vs. 1.75%), aggregate crushing value (20.9% vs. 17.2%), aggregate impact value (28.2% vs 16.78%), and abrasion value (26.1% vs 14.3%). However, these values still fall within acceptable limits for pavement applications.

- Increasing the RCA replacement ratio in geopolymer concrete resulted in a gradual decline in 28-day compressive strength from 40.16 MPa (0% RCA) to 33.52 MPa (40% RCA). Notably, up to 20% RCA substitution achieved the minimum stipulated strength for pavement applications.
- Water absorption of geopolymer concrete increased from 5.2% to 6.8% as RCA content increased from 0% to 40%. All mixes demonstrated water absorption within the specified limit of 7% for structural concretes.
- Abrasion resistance, evaluated through the density of concrete lost, declined with increasing RCA content from 10.82 $cm^3/50cm^2$ for the control mix to 18.01 $cm^3/50cm^2$ for 40% RCA mix. However, all abrasion values remained within acceptable limits for pavement-quality concrete.
- Chloride ion penetrability, assessed through total charge passed, increased with rising RCA proportions from 1687 to 2196 coulombs. Despite this increase, all geopolymer concrete variations exhibited low chloride permeability, indicating adequate durability.
- With the RCA percentage restricted to 20%, the strength, abrasion resistance, and permeability requirements for pavement construction were fulfilled, substantiating the feasibility of using recycled aggregates in geopolymer concrete for this application.

These conclusions highlight the potential for using RCA in geopolymer concrete for pavement applications while acknowledging the trade-offs in performance as RCA content increases. The study suggests that up to 20% RCA replacement can be effectively used without compromising essential properties required for pavement construction.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

PEER-REVIEW

Externally peer-reviewed.

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