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Evaluating the Durability Characteristics of Recycled Aggregate Concrete: A Performance Analysis

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Abstract: The rapid pace of industrialization and population growth has significantly increased the demands placed on the construction industry. The continuous extraction and quarrying of natural aggregates (NA) for construction purposes are leading to the depletion of natural resources, creating a substantial demand for these materials. Additionally, industrialization contributes to the accumulation of large quantities of construction and demolition waste, often ending up in landfills. To mitigate the environmental impact and reduce the dependence on natural resources, there is a growing effort to incorporate recycled aggregates in conventional concrete by partially replacing coarse aggregates with recycled materials. Aggregates, which constitute 70% of the total volume of concrete, are crucial for its strength and stability. The present study investigates the strength properties of recycled aggregate concrete (RAC) by examining M60 grade concrete, where natural aggregates are partially substituted with recycled aggregates. Furthermore, moisture movement—a critical factor affecting the durability of RAC—is analyzed by comparing it with that of normal concrete. To assess the durability properties and determine the suitability of RAC under challenging conditions, tests such as permeability, sorptivity, and Rapid Chloride Penetration Test (RCPT) are conducted on both normal concrete and RAC.

Keywords: Normal concrete (NC), Waste from construction and demolition (C & D), Recycled aggregate concrete (RAC), compressive strength, Sorptivity, permeability and RCPT test.

1. Introduction

The Indian economy is significantly influenced by construction activities, and the ongoing industrial revolution has further escalated the demand for natural resources to meet the needs for construction materials. Embracing the concept of sustainability, which involves reducing, reusing, and recycling materials, is crucial for fulfilling these material requirements while also maintaining an eco-friendly environment. This study focuses on achieving sustainability by utilizing construction and demolition (C&D) waste materials as a replacement for coarse aggregates. The benefits of incorporating waste materials into the construction industry have been widely discussed by various authors [1-2]. This approach not only minimizes the disposal of construction waste into landfills, thus reducing the strain on land resources, but also promotes the effective utilization of available land.

However, when construction waste is used in building reinforced concrete structures, it is essential to prioritize the durability aspect throughout the structure's life cycle. Concrete structures must be designed with sufficient consideration for issues like cracking and moisture ingress, which can compromise the integrity of reinforcing steel. This can be achieved through the proper mix proportioning of concrete ingredients, including cement, fine aggregates, and coarse aggregates, along with the use of supplementary cementitious materials (SCMs) and superplasticizers at an appropriate water-binder (w/b) ratio.

Valeria Corinaldesi et al. [3] have discussed the benefits of including SCMs such as silica fume and fly ash in concrete. Silica fume, a byproduct of silicon and ferrosilicon metal production, and fly ash, a byproduct of thermal power generation, have been shown to improve the strength and durability of recycled aggregate concrete (RAC). The use of these SCMs reduces the pore structure in concrete, thereby limiting moisture movement. Rui Vasco Silva et al. [4] highlighted that the inclusion of fly ash significantly enhances resistance to chloride penetration, making it suitable for concrete exposed to aggressive environments. Additionally, studies have shown that incorporating milled glass waste into RAC improves its durability, particularly in resisting sulfate attacks, due to increased pozzolanic activity.

H.Z. Quan [5] found that recycled aggregate concrete (RAC) has higher permeability compared to concrete made with natural aggregates. This increased permeability is due to the inherent porosity of recycled aggregates. However, the performance of RAC can be enhanced by reducing its porosity, making the study of permeability properties—especially with the addition of supplementary cementitious materials (SCMs)—critically important. Studies have also explored improving RAC properties by carbonating recycled aggregates before their use, which has been shown to reduce the porosity, permeability, and water absorption of RAC by 15% to 40% [6]. Despite these promising results, further research is required to optimize the carbonation process, which currently demands considerable effort. Research indicates that recycled aggregates (RA) generally have lower density and specific gravity compared to natural aggregates (NA). Additionally, RA shows higher impact and abrasion values, and the workability of concrete decreases as the proportion of RA increases, particularly with a constant water-cement (w/c) ratio. As the percentage of NA replaced by RA rises, the mechanical strength and durability of RAC tend to decline. In this study, high-strength recycled aggregate concrete is developed using construction and demolition (C&D) waste materials along with industrial by-products, ensuring a suitable water-binder ratio. Given that moisture movement is a key issue impacting durability, this study focuses on comparing the durability characteristics of normal concrete and RAC. Demolition waste aggregates come from various sources, including old structures that have outlived their usefulness, buildings demolished due to natural disasters, and structures damaged by incidents such as fires and explosions. Additional sources of RA include laboratory waste, renovation and repair projects, as well as waste from construction, industrial, and mining activities.

The study aims to assess the properties of RA derived from C&D waste and to evaluate the permeability, sorptivity, and Rapid Chloride Penetration Test (RCPT) of both normal and recycled aggregate concrete. The objective is to understand the durability of RAC and determine its suitability for use in harsh environmental conditions.

2. Materials and Methods

The study utilized the following materials: Ordinary Portland Cement, fine aggregate (manufactured sand), natural coarse aggregates (NCA), recycled coarse aggregate (RCA), mineral admixture (silica fume), chemical admixture (Aura Mix 400 superplasticizers), and water. The construction and demolition waste used in the study was sourced from a building demolition site on the Ramaiah Institute of Technology (RIT) campus in Bangalore, as shown in Figure 1a. The aggregates were obtained by manually crushing the demolished concrete. To ensure quality, the aggregates were thoroughly cleaned to remove any adhering mortar, as depicted in Figure 1b. After cleaning, the recycled aggregates were dried and used as coarse aggregates in the concrete mixture.

(a) (b)

Figure 1 (a) Demolition site, (b) Crushing/washing of demolished concrete

2.1 Characterization of materials

The characterization of materials was conducted through various tests on both concrete and its raw materials. The tests performed included sieve analysis of coarse aggregates (CA) and fine aggregates (FA), crushing tests, impact tests, bulk density measurements, water absorption tests, and specific gravity determinations for both natural aggregates (NA) and recycled aggregates (RA). All these tests were conducted in accordance with the relevant Indian Standards [7,8], and the results are summarized in Table 1.

Table 1: Test results of Natural and Recycled aggregate

Parameter	Natural Aggregate	Recycled Aggregate
Specific gravity	2.515	2.33
Fineness modulus	5.8	6.13
Crushing value	22.21%	24.60%
Bulk density	Compact state-1589Kg/m^3 Loose state-1470 Kg/m^3	Compact state- 1512 Kg/m^3 Loose state- 1428 Kg/m^3
Impact value	18.57%	24.90%
Water absorption	0.2%	1.6%

From Table 1, it is noted that, the properties of RA are very near to NA. Water absorption of RA is eight times more than the NA, but it is still within the permissible limit of 2%.

Tests on fine aggregate: Sieve analysis and specific gravity tests were performed on fine aggregates.

Tests on Cement: The tests on cement include fineness test, specific gravity, standard consistency and setting time test. All the parameters were ensured to be within the permissible IS limit.

2.2 Mix Design

The raw materials used in the study include:

1. Cement: Ordinary Portland Cement (OPC) 43 grade, manufactured in accordance with IS 8112 [10].
2. Fine Aggregate: Manufactured sand, compliant with IS 383 [8].
3. Natural Coarse Aggregate (NCA): Standard coarse aggregate used in concrete.
4. Recycled Coarse Aggregate (RCA): Aggregates with a size range of 12.5 mm passing and retained on a 4.75 mm sieve.

To achieve the required target mean strength, a suitable water-binder ratio of 0.3 was selected. The quantities of materials were estimated using the Perumal method [9] for various replacement levels of natural aggregate (NA) with recycled coarse aggregate (RCA) at 0%, 25%, 35%, and 45%.

2.3 Tests on fresh Concrete

On fresh concrete, slump and compaction factor tests were conducted in accordance with IS standards to ensure workability [11]. Experimental studies were then carried out to assess the strength of the concrete. Cube, beam, and cylindrical specimens were cast, cured, and tested following the procedures outlined in the relevant IS codes [12]. Figure 2 illustrates the setup used for conducting compression, flexure, and tensile strength tests.

(a) (b) (c)

Figure 2. Test setup for (a) compression, (b) flexural and (c) split tensile strength test

2.4 Tests for durability studies

The durability of concrete refers to its ability to withstand environmental conditions without significant deterioration. Although concrete specimens may show strong performance under controlled laboratory conditions, real-world environments can pose different challenges, leading to potential deterioration and loss of strength in concrete structures. To evaluate the durability of concrete, several tests were conducted in accordance with IS regulations, ASTM standards, and the German Standard DIN 1048:

- Acid Attack Resistance: Acids are highly corrosive and can significantly damage concrete. Hydrochloric acid (HCl) was used in this test to assess the concrete's resistance to acid attack.
- Sulphate Attack Resistance: Magnesium sulphate ($MgSO_4$) was used to evaluate the concrete's resistance to sulphate attack, which can cause expansion and cracking in concrete.
- Chloride Attack Resistance: Chloride ions are a major cause of reinforcement corrosion in concrete. This test is crucial for assessing concrete's ability to resist chloride penetration, which is vital for the longevity of reinforced concrete structures.
- Saturated Water Absorption Test: This test estimates the total pore volume of the concrete. Higher pore volume generally indicates lower durability, as porous concrete is more susceptible to environmental deterioration.
- Sorptivity: Sorptivity measures the ability of concrete to absorb and transport water or other liquids through capillary action. This test helps indicate the potential for water-induced deterioration, as more porous concrete will absorb water more readily.
- Permeability Test: This test measures the rate at which fluids can flow through concrete. Higher permeability suggests lower durability, as it indicates that the concrete is more prone to deterioration.
- Rapid Chloride Ion Penetration Test (RCPT): This test assesses the porosity of concrete by measuring the electrical charge passed through it, providing an indication of the concrete's resistance to chloride penetration.
- Abrasion Resistance Test: This test evaluates the wear resistance of the concrete surface. Lower wear indicates higher durability, as it suggests the concrete can withstand mechanical abrasion over time.

3. Results

To evaluate the fresh properties of concrete, slump and compaction factor tests were performed, and the results met the design specifications. For hardened concrete, tests were conducted to determine compressive strength, split tensile strength, and flexural strength. Additionally, a series of durability tests were carried out to assess the concrete's performance under various environmental conditions. These durability tests included: Acid attack resistance, Sulphate attack resistance, Chloride attack resistance, Saturated water absorption, Sorptivity, Rapid Chloride Ion Penetration Test (RCPT), Permeability, Abrasion resistance. All these tests were conducted on both the control mix (natural aggregate concrete, NAC) and concrete with optimum levels of recycled aggregates (RAC).

3.1. Test results for mechanical properties

The mechanical strength tests of concrete were performed for 3, 7, 14 and 28 days.

3.1.1. Compression Test

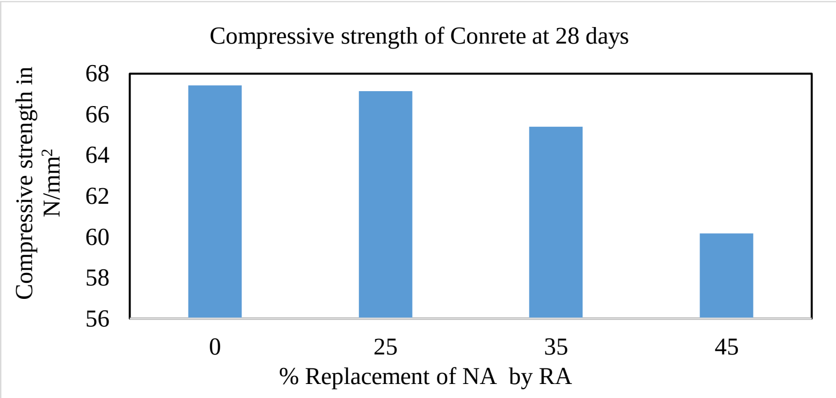

Figure 3. Compressive strength of concrete at 28 days

Figure 3 illustrates the compressive strength of cube specimens with various percentages of natural aggregate (NA) replaced by recycled aggregate (RA) after 28 days of curing. The results show that the maximum compressive strength was achieved with natural aggregate concrete (NAC), which is 67.43 N/mm². Among the recycled aggregate concrete (RAC) mixes, the highest strength was observed with 25% replacement of NA by RA, reaching 67.14 N/mm². This represents a reduction of 0.43% compared to the NAC. Conversely, the lowest strength was found in the 45% replacement mix, with a compressive strength of 60.17 N/mm², indicating a reduction of 10.76% compared to NAC.

3.1.2 Split tensile strength test

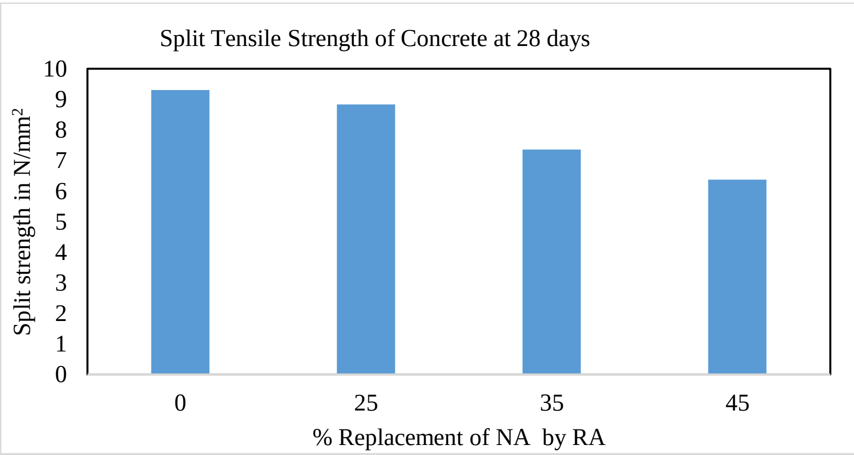

Figure 4. Split tensile strength of concrete at 28 days

Figure 4 presents the split tensile strength of cylindrical specimens with various percentages of natural aggregate (NA) replaced by recycled aggregate (RA) after 28 days of curing. The results reveal a decreasing trend in tensile strength as the percentage of RA increases. The maximum split tensile strength of 9.3 N/mm² is observed for natural aggregate concrete (NAC). Among the recycled aggregate concrete (RAC) mixes, the highest tensile strength of 8.83 N/mm² is achieved with 25% RA replacement, representing a reduction of 5.05% compared to NAC. Conversely, the lowest tensile strength of 6.37 N/mm² is recorded for the 45% RA replacement mix, showing a significant reduction of 31.5% compared to NAC.

3.1.3 Flexure test

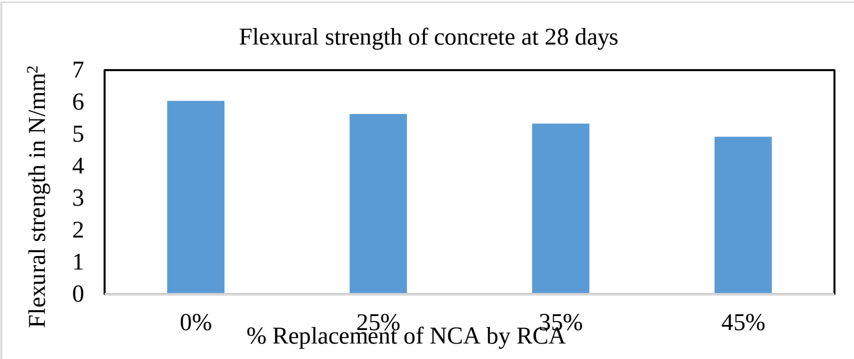

Figure 5. Flexure strength of concrete at 28 days

Figure 5 shows the flexural strength of prism specimens with various percentages of natural aggregate (NA) replaced by recycled aggregate (RA) after 28 days of curing. The results indicate a decreasing trend in flexural strength with increasing RA replacement.

The flexural strength for natural aggregate concrete (NAC) is 6.04 N/mm². Among the recycled aggregate concrete (RAC) mixes, the highest flexural strength of 5.63 N/mm² is observed with a 25% RA replacement, which represents a reduction of 6.8% compared to NAC. The lowest flexural strength of 4.92 N/mm² is recorded for the 45% RA replacement mix, showing an 18.54% reduction compared to NAC.

3.2. Test results for durability

3.2.1 Acid resistance test

Figure 6 depicts concrete cubes immersed in hydrochloric acid (HCl) solution to assess the acid attack resistance of natural aggregate concrete (NAC) and recycled aggregate concrete (RAC). Figure 7 illustrates the percentage of weight loss after exposure to the acid attack for both NAC and RAC, highlighting the severe degradation experienced by the concrete under acidic conditions. The results indicate that weight loss increases with the age of the concrete, reflecting greater degradation over time. Notably, RAC shows a more significant weight loss compared to NAC, demonstrating that recycled aggregate concrete is more susceptible to deterioration when exposed to an acidic environment.

Figure 6. Concrete cubes immersed in HCl solution

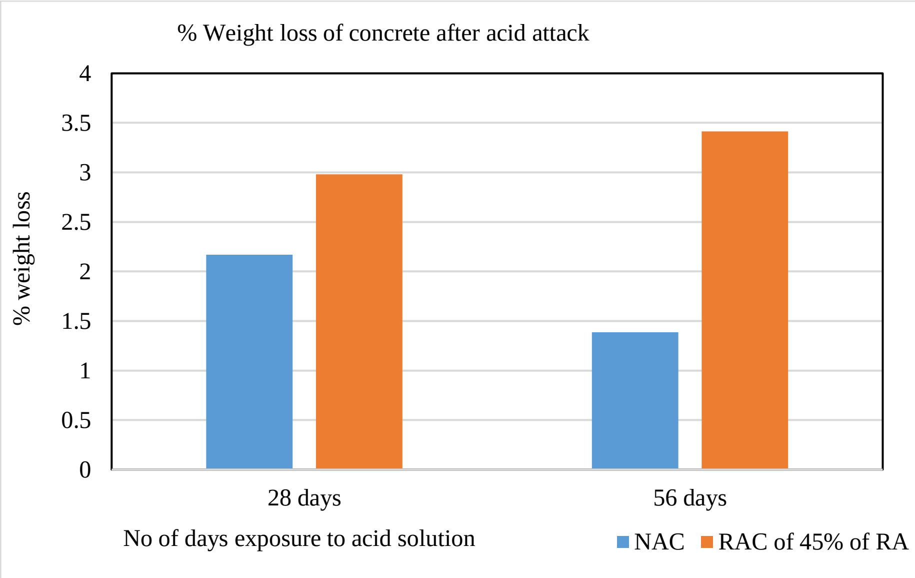

Figure 7. Percentage weight loss in NAC and RAC after acid attack

3.2.2 Sulphate attack test

Figure 8. Concrete cubes immersed in magnesium sulphate solution

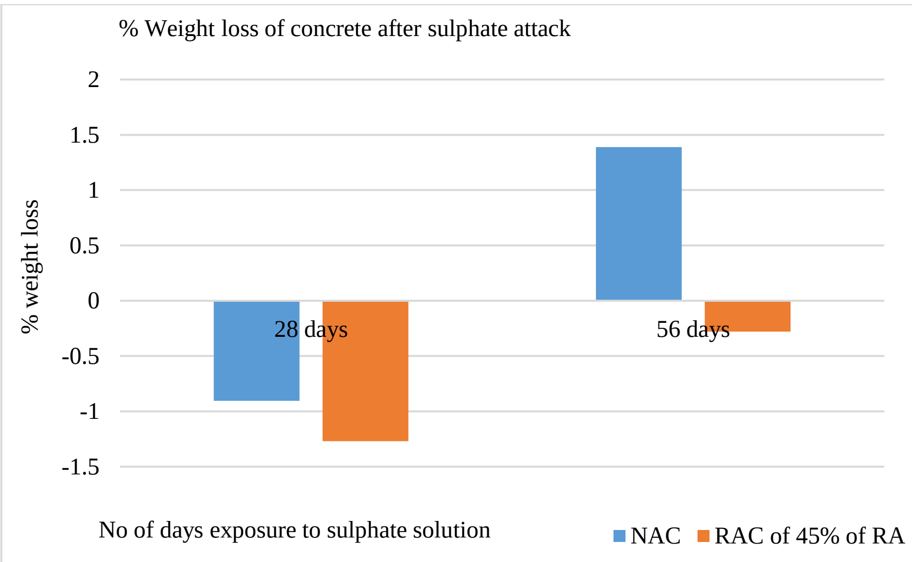

Figure 9. Percentage weight loss in NAC and RAC after sulphate attack

Figure 8 illustrates the sulphate attack test on natural aggregate concrete (NAC) and recycled aggregate concrete (RAC), where the specimens are immersed in a magnesium sulphate solution. Figure 9 displays the percentage weight loss or gain for both NAC and RAC after exposure to the sulphate solution. The results show that both NAC and RAC specimens experienced weight gain when immersed in the sulphate solution. Notably, RAC exhibited a greater weight gain compared to NAC. However, after 56 days or more of exposure to the sulphate solution, a reduction in weight is observed, indicating that the concrete has undergone significant changes or deterioration over time.

3.2.3 Chloride attack

Figure 1 (a) Demolition site, (b) Crushing/washing of demolished concrete

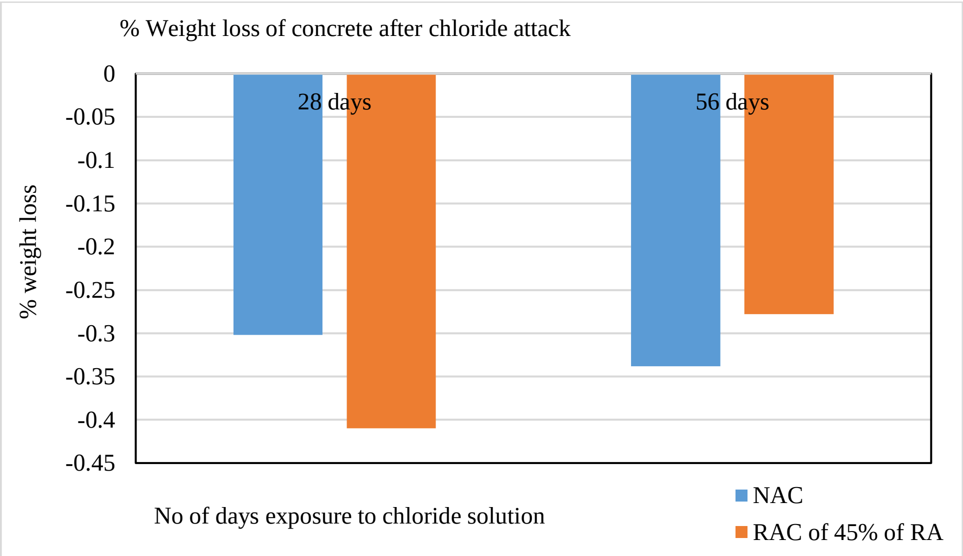

Figure 11. Percentage weight loss in NAC and RAC after chloride attack

Figure 10 shows natural aggregate concrete (NAC) and recycled aggregate concrete (RAC) specimens immersed in a sodium chloride (NaCl) solution to test for chloride attack. Figure 11 presents the percentage of weight loss or gain in both NAC and RAC after exposure to the chloride solution. The results indicate that after 28 days of immersion in the chloride solution, there is an increase in the weight of both NAC and RAC specimens. However, after 56 days of immersion, the weight gain observed at 28 days is reduced. RAC shows a greater weight gain compared to NAC. Additionally, the compressive strength of the concrete was evaluated after exposure to hydrochloric acid, magnesium sulphate, and sodium chloride solutions for 28 and 56 days. The results reveal slight variations in compressive strength across these different conditions and durations.

3.2.4 Water absorption test

Based on the tests on NAC and RAC, the water absorption of NAC and RAC is 0.2% and 1.6%. The water absorption of RAC is 8 times that of NAC, this is due to the adhering mortar found in recycled aggregates, which has a tendency to absorb excess water.

3.2.5 Sorptivity test

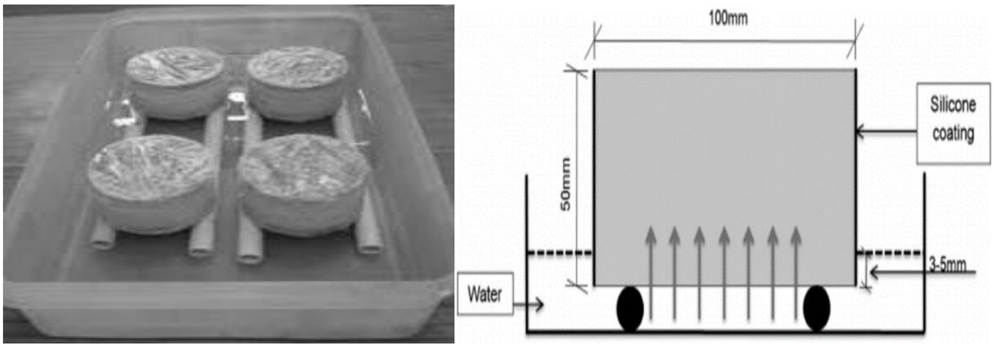

Figure 12. Sorptivity test for NAC and RAC

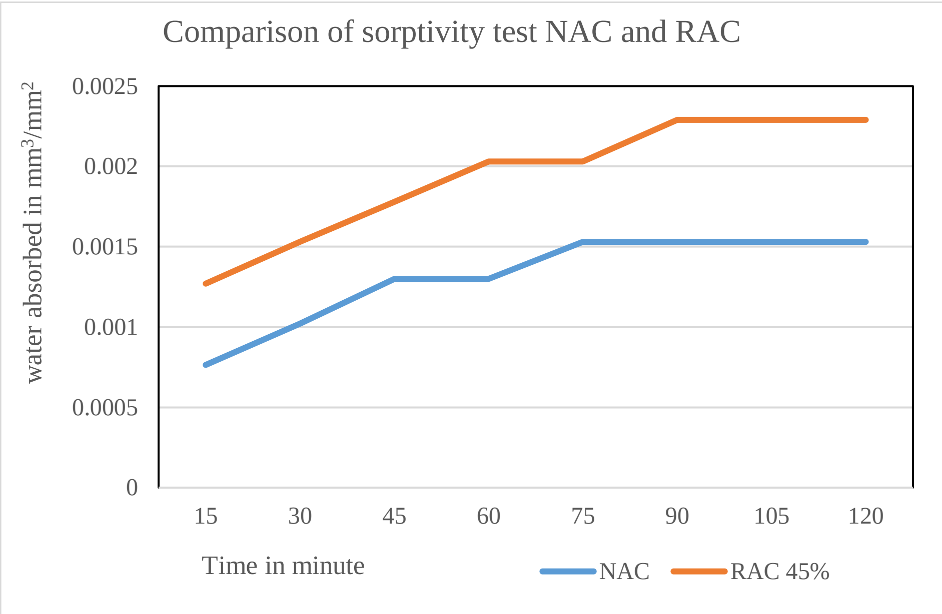

Figure 13. Comparison of sorptivity test for NAC and RAC

Figure 12 displays the setup used for the sorptivity test on natural aggregate concrete (NAC) and recycled aggregate concrete (RAC). Figure 13 shows the results of the sorptivity test for both types of concrete. The results indicate that RAC exhibits higher water absorption compared to NAC. This increased water absorption in RAC is attributed to the adhering mortar present in the recycled aggregates, which tends to absorb more water through capillary suction.

3.2.6 Rapid chloride ion penetration test

Figure 14, shows the RCPT test on RAC. RCPT rating is considered as per ASTM C1202. [13] From test results, the total charge passed through RAC of 45% RA is 1145 coulombs which depicts low permeability

Figure 14. RAC Specimens under RCPT testing

3.2.7 Permeability test

Figure. 15, Shows the permeability test on RAC as per DIN-1048 part 5-1991 [14]. It is observed from the results that for RAC of 45% replacement, only 2mm of water penetration was noticed indicating it is low permeable.

Figure 15. RAC Specimens for permeability test

3.2.8 Abrasion resistance test

Figure 16. shows that abrasion test on RAC as per IS: 1237-2012 [15]. For the RAC of 45% replacement, 2.46mm of wearing of the surface is observed

Figure 16. RAC Specimens under abrasion testing

4. Discussion

Here's a summary of the key findings:

- **Material Characterization**: The characterization results supported the integration of construction and demolition (C&D) waste into the production of recycled aggregate concrete (RAC). Perumal's method was used for the mix design of M60 grade concrete.

- **Mechanical Strength**: Increasing the percentage of recycled aggregate (RA) in place of natural aggregates (NA) leads to a reduction in mechanical strength (compressive, tensile, and flexural). Strength reduction is minimal up to 35% RA replacement, which seems to be an optimal replacement level. At 45% RA replacement, strength is reduced by about 13% compared to the target mean strength, warranting further durability studies.

- **Durability**: The compressive strength of RAC and NAC after exposure to acid, sulphate, and chloride attacks were comparable and within allowable limits. Both NAC and RAC experienced about 50% strength loss in these conditions. RAC with 45% RA replacement shows poor acid resistance but maintains good resistance to sulphate and chloride environments.

- **Water Absorption and Sorptivity**: RAC exhibits about 1.4% higher water absorption than NAC at 28 days, attributed to the adhering mortar in recycled aggregates. The sorptivity test confirms higher water absorption for RAC, but it remains within acceptable limits.

- **Rapid Chloride Penetration Test (RCPT)**: RAC shows low chloride ion permeability, though NAC exhibits very low permeability.

- **Permeability and Abrasion**: The average depth of water permeability for RAC is 2 mm compared to 1.60 mm for NAC, both within permissible limits. Abrasion resistance shows a surface wear of 2.46 mm, which is acceptable.

Overall, RAC with 45% replacement of NA demonstrates satisfactory durability and performance, making it a viable option for sustainable concrete construction.

5. Conclusions

Here are the conclusions drawn from the present study:

Material Characterization: Thorough material characterization is essential when using construction and demolition (C&D) waste. The characteristics of the aggregates used in this study were within acceptable limits, making them suitable for use in M60 grade concrete.

Mechanical Strength: Mechanical tests revealed that increasing the percentage of recycled aggregate (RA) replacement leads to a decrease in concrete strength. Among the tested replacement ratios, 45% RA replacement was found to be the most suitable for maintaining structural integrity in M60 grade concrete.

Durability: Durability tests showed that recycled aggregate concrete (RAC) has 1.4% higher water absorption compared to natural aggregate concrete (NAC), attributed to the adhered mortar on recycled aggregates. This issue can be mitigated by treating the recycled aggregates before use. RAC with up to 45% RA replacement performs within acceptable limits for sorptivity, Rapid Chloride Penetration Test (RCPT), and permeability, though it shows some limitations in acid resistance.

Sustainability: RAC with 45% RA replacement meets both strength and durability criteria, making it a viable option for structural concrete. The use of RAC contributes to sustainability in construction by reducing reliance on natural aggregates and promoting recycling of C&D waste.

Overall, RAC with a 45% replacement ratio is suitable for use as structural concrete, balancing durability, strength, and sustainability in construction practices.

Author Contributions: B. Suguna Rao, Chandrakanth and S M Naik were involved in the executing the concept involved in the current work, combined effort has framed and worked towards the methodology involved in the current work and secured the necessary resources and have completed the project and have together worked on the draft of the paper. “All authors have read and agreed to the published version of the manuscript.”

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Conflicts of Interest: “The authors declare no conflict of interest.” With respect to the research, authorship and publication of the article.

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