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"Sustainable Concrete With Recycled Aggregates And Fiber-Reinforced Plastic Waste: Experimental Study On Strength, Durability, And Cost"

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Abstract
Concrete is presently the most common building materials in the world, but due to its natural aggregate composite requirements and cement manufacturing, it is playing its significant role to exhaust natural resources and to cause greenhouse emissions. In solving these sustainability issues, the paper explores the possibility of using the Recycled Concrete Aggregate (RCA) and Fiber-Reinforced Plastic (FRP) waste as a partial replacement of natural coarse aggregates in M25-Grade concrete. The project will seek to consider the mechanical and the durability factors of such sustainable mixes and establish whether they are economically viable to come up with an optimum level of replacement. Concrete mixes of 0, 10, 20 and 30 percent RCA-FRP combi replacements were prepared respectively. Some experimental tests were carried out: compressive strength at 7 and 28 days, water absorption, acid resistance according to the specifications of the IS and cost analysis based on DAR 2023 rates. It was found that, the control mix exhibited the maximum 28-day composite strength (31.15 N/mm^2) followed by the 10 percent and 20 percent replacement mixes which reduced by 6.6 percent and 14.4 respectively but qualified the IS 456:2000 requirements. The proportion of 30 per cent fell to 24.36 N/mm^2 which is lower than the structural strength of M 25. Higher water absorption ranging between 2.40 and 3.03 percentage points was observed with an increase in the content of the RCA-FRP without exceeding the limit of 5 per cent. There was a display of 3-16 percent loss of strength due to exposure to acid but mixes up to 20 percent showed good resistance to it. At 30 percent replacement, the economic evaluation implied a cost saving of 3.3 percent. This implies that even at increment up to 20 percent of replacement one can find the best mix of structural performance, life and economics, which is a realistic way forward in pursuing sustainability in construction at the same time stepping down waste and saving resources.
Keywords - Cost Analysis, Compressive Strength, Durability Performance, Fiber-Reinforced Plastic (FRP), Recycled Concrete Aggregate (RCA), Sustainable Concrete.

1. INTRODUCTION
Concrete is still the core of the contemporary building industry, but its impact on the environment is increasingly becoming a problem because of excessive use of natural resources and large volumes of CO_2 emissions during the production of cement (Phoeuk & Kwon, 2023; Siddika et al., 2021). Concrete consumption in the world quantified in billions of tones per year has caused depletion of resources, large amounts of energy use in production and environmental destruction (Belay & Woldesenbet, 2022; Lima et al., 2022). Recycled concrete aggregates (RCA) and fiber-reinforced plastics (FRP) as a sustainable solution have been used to alleviate the situation and promote the circular economy behaviors. (Su & Xu, 2023; B. Wang et al., 2021).
RCA is a waste product of the construction and the demolition waste, which substitutes the natural aggregates and diverts the landfills (Ma et al., 2023; P. Wang et al., 2016). Nevertheless, its application tends to make its structures less resistant to compressions, and be more porous because of enmeshed mortar and poor interphase regions (Dawood, M. H., 2023; Jagadesh et al., 2024). FRP, in its turn, is a lightweight durable, non-rusting substitute to steel reinforcement and enhances tensile strength and resistance to wear. (Belay & Woldesenbet, 2022; Xiong et al., 2020). Recently, it has been shown that

RCA in combination with FRP may even partially compensate mechanical disadvantages of RCA concrete and improve ductility and crackability (Gao et al., 2024; Saadi et al., 2025; Sinđić Grebović & Grebović, 2024).

Experimental evidence confirms this synergy: (Saadi et al., 2025) developed CFRP-RCA beams with a maximum of 198.4 kN strength, however, brittle failure is still a problem,, while(Fu et al., 2024) reported high flexural toughness of waste GFRP fibers. Similarly, PET fibers in SCC with RCA improved tensile strength by 28%(Bayah et al., 2024), and hybrid fibers enhanced ductility and energy absorption (Gao et al., 2024). These advances though rely extensively on ideal RCA-FRP ratios which have not yet been standard. (Htet et al., 2024; Sinđić Grebović & Grebović, 2024). Moreover, harsh environment life and sustainability as well as economic viability of a lifecycle are scarcely investigated (Dada et al., 2024; Raza et al., 2024).

This research study tries to fill these gaps through performance evaluation of M25-grade concrete with different percentages of blending of RCA and FRP waste on its mechanical and durability performance. All the tests conducted are: Compressive strength (7 and 28 days), water absorption, and an acid resistance test with an economic feasibility study of determination of cost effective, structurally and environmentally viable mix designs of real applications.

2.METHODOLOGY

The methodology involves characterization of the material used, preparation of mix design, casting and curing of specimens to be tested along with carrying out an experimental evaluation using the compressive strength, water absorption, and acid resistance test. Moreover, an economic report was prepared that was used to determine the feasibility of costs.

2.1 Materials

- Cement:

OPC of 53 Grade which meets the specifications of IS: 12269-1987 was employed. The cement had a specific gravity of 3.15 and met all the standards of initial and final setting time.

- Fine Aggregate:

As fine aggregate, river sand was used that performed a 4.75 mm is sieve. The specific gravity was found to be 2.65 and water absorption as per IS: 2386 (Part 3) was found to be in range.

- Natural Coarse Aggregate:

Crushed aggregates of 20 mm nominal size were used as a reference aggregate.

- Recycled Concrete Aggregate (RCA):

RCA was crushed, cleaned and sieved to 20 mm) size and was sourced in demolition waste.

- Fiber Reinforced Plastic (FRP):

Waste FRP fibers obtained from construction scrap. These fibers were added to enhance ductility and crack resistance.

- Water:

Potable water without impurities was applied on both mixing and curing.

2.2 Mix Design

The concrete mix was intended to meet the M 25 grade as per IS: 10262 caution 2019 with target strength of 31.6 Mpa and water cement ratio of 0.50. The mix ratio of control specimen was:

Cement: Fine Aggregate: Coarse Aggregate = 1: 1.92: 2.93, Water-cement ratio = 0.50

2.3 Replacement Levels:

Four mixes were prepared by partially replacing natural coarse aggregate with RCA and FRP waste in combined percentages:

- 1 (Control): 0% (RCA + 0% FRP)
- 2: 10% (RCA + FRP)
- 3: 20% (RCA + FRP)
- 4: 30% (RCA + FRP)

(The FRP was included as part of the RCA proportion by weight, maintaining total aggregate content constant.)

2.4 Specimen Preparation

To determine the compressive strength at 7 and 28 days 36 cube specimen of dimension 15 x 15 x15 cm were cast. On every batch, 9 cubes (3 each) were made (7-day, 28-day, and durability tests).

- Concrete was made with the aid of a mechanical mixer.
- The mix was poured in 3 portions of oiled steel molds and each layer compacted using a tamping rod.
- A specimen was demolded after 24 hr and immersed in water bath at 27 ± 2°C until to the time of the test.

2.5 Testing Procedures

All tests were performed as per Indian Standard specifications:

2.5.1 Compressive Strength Test

- Conducted on CTM machine of 2000 kN capacity according to IS: 516–1959.
- Cubes were tested at 7 days and 28 days.
- Strength calculated as:

F_{ck}= {P}/{A}

where P = load at failure (KN), A = cross-sectional area (mm^2).

2.5.2 Water Absorption Test

- Carried out as per IS: 2386 (Part 3)–1963.
- Dry cubes were weighed (W_1), immersed in water for 24 hours, reweighed (W_2), and water absorption (%) computed as:

Water Absorption (%) =W2−W1/W1×100

2.5.3 Acid Resistance Test

- Specimens immersed in 5% H_2SO_4 solution for 28 days after curing.

2.6 Economic Analysis

A rate analysis computed utilizing material costs and RCA and FRP inclusion, was done using CPWD Schedule of Rates (DAR 2023). Comparisons of cost per cubic meter of concrete between each mix were made to realize economic viability.

3.Evaluation of Mechanical Properties

According to the previous studies, the substitution of natural aggregates with the RCA usually leads to the decrease of compressive strength, which can be explained by adhered mortar, high porosity, and microcracking coined by the RCA use (Dawood, M. H., 2023; Jagadesh et al., 2024). These variations in the strength are greatly affected by factors like curing conditions and quality of RCA (Ma et al., 2023; Rattanachu et al., 2020).

The experiments conducted recently revealed the fact that it is possible to obtain compressive strengths that can rival the average concrete ones through the use of RCA combined with the FRP-based reinforcement, where the levels are optimized. For example, (Saadi et al., 2025) reported peak load capacities of 198.4 kN in CFRP-RCA beams, while (Sinđić Grebović & Grebović, 2024) demonstrated that the capacity of mixes with RCA and fiber to perform as well as natural aggregate concrete in strength and ductility was established. However, excessive FRP or RCA can lead to mix heterogeneity and strength reduction (Htet et al., 2024; Kryeziu et al., 2023).

Although all these developments have been witnessed, the ideal proportion of RCA and the FRP and standardized performance levels have not been established. To reduce this difference, the proposed research would test the compressive properties of concrete mixes graded M25 at 7 and 28 days on the replacement of RCA-FRP of 0%, 10%, 20%, and 30% replacement, to find the most suitable combination which will satisfy sustainability potential and mechanical stability.

3.1 Design and Testing Summary

The experimental program consisted of the composition of four mixes of concrete with a partial replacement of natural coarse aggregate (NCA) of Recycled Coarse Aggregate (RCA) and Fiber Reinforced

Polymer (FRP) waste with emphasis on various proportions. The mixes were of equal volumes of cement of 1.87 kg and sand of 2.08 kg in which NCA was progressively replaced in the following manner:

- Control Mix (0% Replacement): Used 3.90 kg of NCA without any RCA or FRP addition.
- 10% Replacement Mix: Contained 3.51 kg NCA, 0.195 kg RCA (5%), and 0.195 kg FRP (5%).
- 20% Replacement Mix: Included 3.12 kg NCA, 0.390 kg RCA (10%), and 0.390 kg FRP (10%).
- 30% Replacement Mix: Incorporated 2.73 kg NCA, 0.585 kg RCA (15%), and 0.585 kg FRP (15%).

The compressive test and water absorption was done according to IS 516:1959 and the IS 2386 (Part III):1963 respectively. The acid resistance test was intended to determine the amount of strength loss of the specimen under the aggressive reaction with acids. These tests present the full picture of the performance of RCA and FRP-based concrete concerning mechanical strength and durability properties.

3.2 Compressive Strength Results

Table 1 Compressive Strength Testing Results (7 Days)

Replacement Percentage	7 Days KN			Average	Load
	1	2	3		N/MM2
Normal (0) %	510	522.6	502.4	511.67	22.74
RCA (5%) & FRP (5%) = 10 %	445.7	420.5	430.5	432.23	19.21
RCA (10%) & FRP (10%) = 20 %	425.7	410.3	390.8	408.93	18.17
RCA (15%) & FRP (15%) = 30 %	375.2	350.7	365.2	363.70	16.16

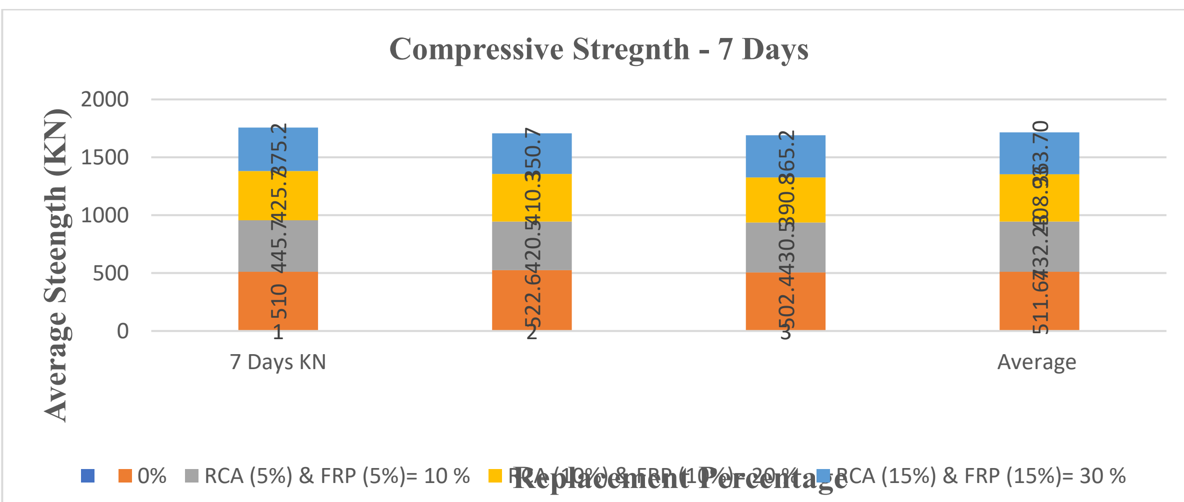

Fig. 1 Compressive Strength Test Results (7 Days)

Table 2 Compressive Testing Results (28 Days)

Repalcement Percentage	28 Days KN			Average	Load
	1	2	3		N/MM2
Normal (0) %	702.3	690	710	700.77	31.15
RCA (5%) & FRP (5%) = 10 %	660.7	647.2	655.9	654.60	29.09
RCA (10%) & FRP (10%) = 20 %	595.6	610	593	599.63	26.65
RCA (15%) & FRP (15%) = 30 %	538.7	545.5	560.2	548.13	24.36

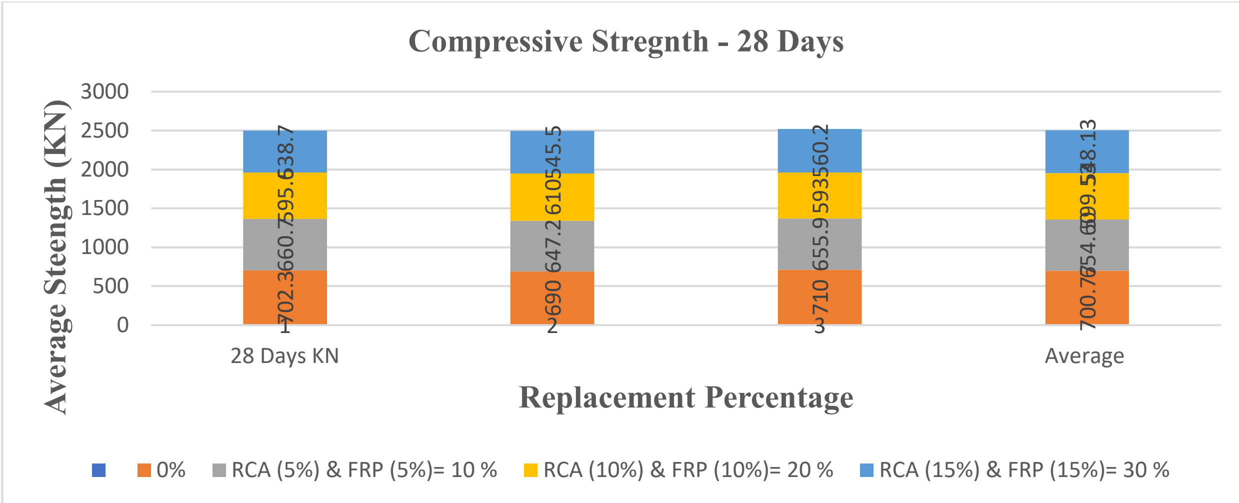

Fig. 2 Compressive Strength Test Results (28 Days)

The results of the compressive strength show a steady decline in performance as the RCA and FRP replacement increase (Fig 1 and Fig 2). On day 7, the control mix obtained the highest strength that was 22.74 N/mm 2 whereas, mixes with 10, 20, and 30 replacement percentages had strengths of 19.21 N/mm 2, 18.17 N/mm2, and 16.16 N/mm2, which reflected as high as 28.9 percent less than the control mix. Likewise, after 28 days control mix had the highest value of 31.15 N/mm2 which was within the limit of M25 whereas 10% and 20% replacements had slight declines of 29.09 N/mm2 (6.6%) and 26.65 N/mm2 (14.4), respectively, still sufficient to meet the structural requirements. But when the replacement percentage changed to 30%, the strength decreased down to 24.36 N/mm2, which was lower than the requirement of M25. The trends imply that 20% replacement would be the maximum amount used practically to preserve the structural performance because increased RCA and FRP percentage will harm bond performance, mix homogeneity, and density (See Table 1 and 2) .

4. Durability Analysis

4.1 Water Absorption

The durability is a significant parameter of concrete civil engineering structure under aggressive environment and influences the life time of the structures and the performance of the structures during long-term operation. Porosity may be increased by water absorption, and toughness may be reduced upon use of Recycled Coarse Aggregate (RCA) in either acidic climates or chloride-affected climates (Huang et al., 2024). However, such disadvantages are fully mitigated through incorporation of Fiber-Reinforced Polymer (FRP) materials that enhance a far fewer propagation of cracks, improved permeability and an enhanced resistance to chemical attack. It has been reported that, an FRP-impregnated concrete was stronger by at least 8-15 percent exposed to an acid solution as compared to 15-25 percent increase in its motile concrete, denoting its performance in acid resistance is enhanced (Huang et al., 2024). Following the same has been the effect water absorption in RCA based concrete which usually is 10-20% percent more than its conventional counterparts and reduction in such a dimension is achieved due to the nature of bridging network that is established within the matrix when FRP is incorporated in it. (Abdo, M., Toumpanaki, E., Diambra, A., & Bank, 2024). Moreover, in the FRP composites, the ingress of chloride which plays a major role in the corrosion of steel is not a much of a problem, as FRP material is resistant to corrosion; reduction in penetration of the chloride ions by 60-80% has been shown when the FRP wrapping technique is used in steel corrosion protection applications (Zhang et al., 2024). These findings collectively indicate that partial RCA and FRP integration enhances durability, making it suitable for sustainable and resilient concrete design (See Table 3).

Table 3 Water Absorption (28 Days)

Replacement Percentage	Cube ID	Dry Weight (g)	Wet Weight (g)	Water Absorption (%)	Avg Water Absorption

Normal (0) %	C1	7910	8090	2.28	2.40
	C2	7880	8081	2.55	
	C3	7968	8158	2.38	
RCA (5%) & FRP (5%) = 10 %	C4	7796	8026	2.95	2.61
	C5	7845	8069	2.86	
	C6	8090	8254	2.03	
RCA (10%) & FRP (10%) = 20 %	C7	7758	8043	3.67	2.76
	C8	7889	8030	2.03	
	C9	7851	8053	2.57	
RCA (15%) & FRP (15%) = 30 %	C10	7923	8150	2.87	3.03
	C11	8007	8260	3.15	
	C12	8063	8312	3.09	

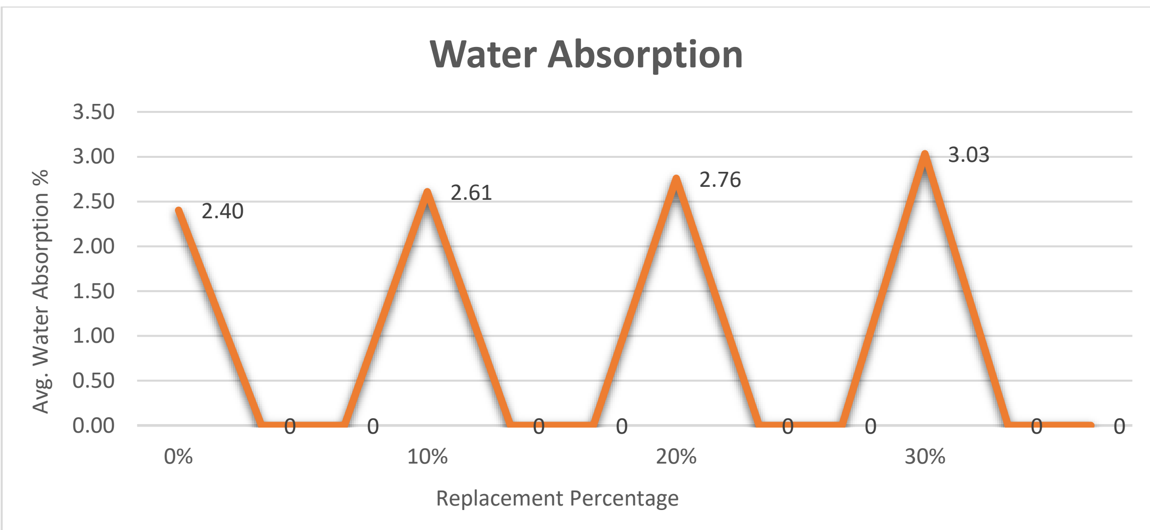

Fig 3 Average Water Absorption (28 Days)

The water absorption results indicated that porosity is also increasing gradually with increase of RCA and FRP level. The control mix registered the least absorption of 2.40% which depicts a dense microstructure whereas 10%, 20%, and 30 percent replacement percentage comprises a gradual increase to 2.61, 2.76, and 3.03 percent, respectively. The pattern depicts that the porosity of RCA and mortar bonded in it by glue, along with the clumping of fibers of FRP, adds to a slight seepage in permeability. Nevertheless, all the values are much less than the imposed limit of 5 %, which is 4,000 5,000 IS 456:2000 and ASTM C642, thus that the durability is acceptable even at 30 per cent replacement (See Fig 3).

4.2 Acid Resistance Test

As indicated in Table and Figure, the results obtained during the acid resistance test show the efficiency of different proportions of Recycled Coarse Aggregate (RCA) and Fiber-Reinforced Plastic (FRP) concrete mixes against aggressive chemical attack (H2SO4). Control mix (0% replacement) was the compound mix entered with the highest compressive strength of 26.65 N /mm2 after 28 days of the exposure of acid on the average load of 599.60 kN. A similar slight decrease in strength was recorded at 25.60 N/mm 2 when 10 percent replacement (RCA 5% + FRP 5%) was carried out; hence, a 3.95 percent reduction in strength relative to control was recorded.

Moreover, when the replacement was 20 percent the strength dropped to 24.20 N/mm 2 representing a drop of 9.2 percent. The lowest strength was recorded at 30 percent replacement mix with the strength of 22.33 N/mm 2 reflecting the total loss of 16.2 percent as compared to that of the control mix. The trend also proves that the skewness of the acquired values signify that the porosity of concrete is raised and the acid resistance was reduced by the higher values of replaced levels that is owed to porous nature of RCA and poor bonding of the FRP particles. However, the durability of mixes containing 10 and 20 percent replacements was acceptable and they performed nearly like the regular concrete in terms of performance in research findings made by the similar studies (Huang et al., 2024; Zhang et al., 2024).(Huang et al., 2024; Zhang et al., 2024).

Table 4 Compressive Strength Acid Resistance (28 Days)

Replacement Percentage	28 Days KN (Acid Resistance)			Average	Load
	1	2	3		N/MM2
Normal (0) %	590.8	598	610	599.60	26.65
RCA (5%) & FRP (5%) = 10 %	572.1	587.3	569	576.13	25.60
RCA (10%) & FRP (10%) = 20 %	545	548.4	540	544.47	24.20
RCA (15%) & FRP (15%) = 30 %	504	502	501.3	502.43	22.33

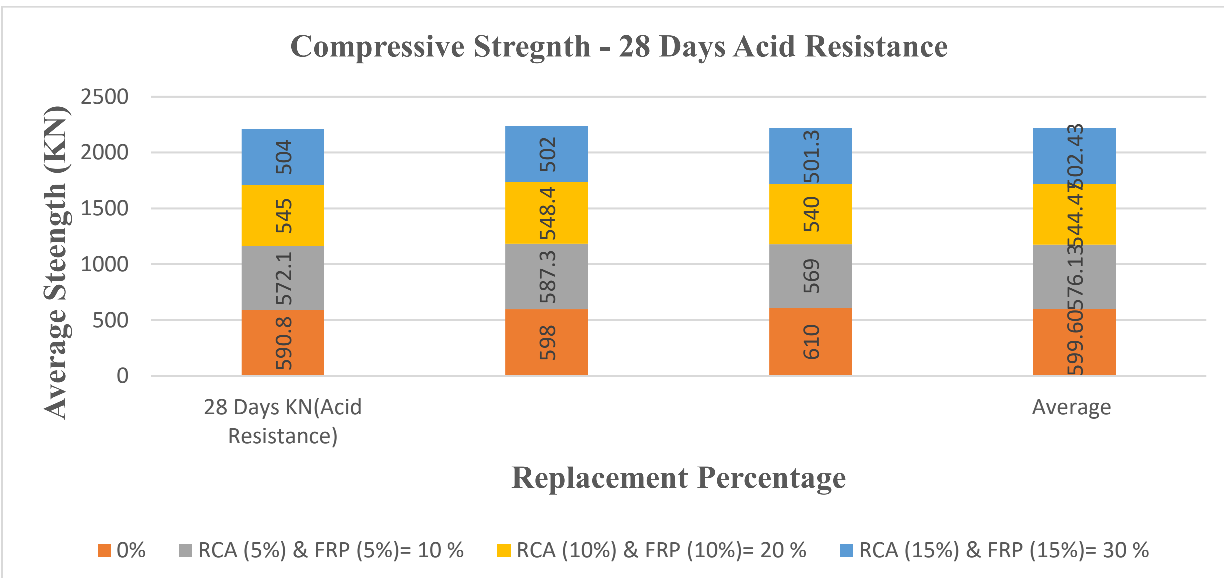

Fig 4 Compressive Strength Acid Resistance (28 Days)

On the whole, the findings reveal that the predetermined inclusion of RCA and FRP (up to 20%) can be deemed as being appropriate when it comes to the application of concrete with the goal of promoting sustainability without making compromises on the durability of the product when subjected to acidic conditions(See Table 4).

5. Economic Study

5.1 Economic Study of Concrete: Insights from Recent Literature

The construction industry still regards concrete as a major element due to its flexibility, durability and strength. However, its economic impacts in production and on the sustainability have catalyzed a massive research. According to the existing researches, life-cycle cost analysis (LCCA) serves as the crucial tool to embrace both financial and environmental considerations. Such an approach does not only reflect the initial spending but it also reflects operating, maintenance, and end of life-costs which dictate the long-term viability of any financial nature.

Key findings from literature include:

- Life Cycle Cost Savings- Recycled concrete aggregates (RCA) as well as fly ash and filtered waste water are used in providing a mixture that saves cost as well as impacts to the natural environment. According to (Abushanab & Alnahhal, 2023), the life cycle costs of a cost are decreased by 15 to 10 percent, in case of such application of RCA and environmentally friendly replacements.

- Precast and Modular Construction- Overall, the precast construction is incredibly costfill because it reduces the labor and indirect costs per project by about 20 percent; thus, it suffices in building large-scope projects, considering the study of which examines 38 projects.(Wong & Loo, 2022).
- Innovative Mix Designs to reduce Costs- (Shaker et al., 2020) examined locally-produced concretes with elevated water-cement proportion and situational aggregates and discovered that by 8-12 percent cost reductions were made whereby the difference had a minor impact on compressive power.
- Green Concrete- Geopolymer and Green Concrete- The research (Akhtar et al., 2022; Verma et al., 2022), as per which, the utilization of geopolymer concrete contributes not only to the considerable decrease in the emission of CO_2 but also moaning in preserving economic competitiveness, which is especially worthwhile considering the matters of the presence of industrial wastes, including fly ash, in the neighbor.
- Waste Management and Circular Economy- (El-Shaboury et al., 2019) highlighted the economic opportunities of recycling of concrete waste that reduces the cost of landfill and delivers an alternative source of the aggregate that can reduce aggregate expenses by up to 25 percent during the purchases.
- Cold Climates and Harsh Environments- (Chen et al., 2020) discussed the topic of curing practices in low temperature conditions, and their conclusion held that the short term expenses are justified by long term economic and structural attractions of carrying out such processes.
- Innovative Methods of Construction-(Han et al., 2021) arrived at a conclusion that 3D concrete printed buildings manufactured by recycled aggregates used have economic advantages of 15-20 percent in comparison with conventional constructions in regards to labor, form costs savings.

5.2 Replacement Strategy and Economic Evaluation

The analysis has been done based on the usage of the waste product, Recycled Coarse Aggregate (RCA) and Fiber Reinforced Plastic (FRP) in M25 concrete by replacing the natural coarse aggregates with partial percentages. This was substituted in mixed proportion of RCA (5 percent) & FRP (5 percent) = 10 percent, RCA (10 percent)-FRP (10 percent) = 20 percent and RCA (15 percent)-FRP (15 percent) = 30 percent as the aggregate percentage to be utilized in the mix. With this solution, it is possible to retain the structural performance with the adoption of sustainable materials.

The rate analysis of 1m3 of concrete produced at each level of replacement was incorporated in the cost of the material, the cost of carriage of RCA and FRP, labour costs and the overhead costs to measure the economic factor. The cost of the natural aggregates was reduced in proportion to the percent degree of replacement and other expenses including that of transporting RCA and FRP were summed up. The base cost of conventional concrete (0 percent replacement) was compared with the cost of the 10 percent, 20 percent and 30 percent replacement to not only find out how much they cost less and are economically possible but also as a way of checking the initial result once again. In an analysis, the reasons to choose the use of waste materials in a cost optimization and realization of environmental benefits and a lesser direct effect in the concrete performance are outlined.

5.3 Inclusion and Exclusion Criteria

The rate is made with the cost of all concrete materials such as cement, fine aggregates (sand), coarse aggregates (stone) and water inclusive. It also includes mixing, moving and pouring the concrete in its place, shaking or pounding it in the ground with the goal to see to it that the square root of the production is consolidated well with the required time of curing. But the rate does not accommodate centering and shuttering (formwork) which are the temporary structure such as wooden or steel boards, props, and staging, that is applied to shape the concrete until it begins to solidify. And it does not include finishing like plastering, rendering or any other surface treatment into the structural needs. Likewise, the cost of reinforcement-to be covered by the steel bars in RCC which includes cuts, bending, placing and binding, does not form part of the rate and should be included elsewhere in the Bill of Quantities (BOQ).

5.4 Economic Calculations

Table No 5 Economic Calculations

Replacement Percentage	Cost For 1 CUM
Normal 0%	11703
RCA (5%) & FRP (5%) = 10 %	11572
RCA (10%) & FRP (10%) = 20 %	11442
RCA (15%) & FRP (15%) = 30 %	11312

*(Note: All calculations are based on DAR 2023)

Fig 5 Cost Comparison

A similar study of the price of M25 grade concrete at different replacement levels indicates that the prices, at which the concrete is examined per cubic meter, drops gradually with the addition of recycled concrete aggregate (RCA) and fiber reinforced polymer (FRP), level by level (See Table 5). When normal concrete is involved, the price per 1 cum will cost ₹ 11,703/- At the incremented rate of replacement (RCA 5% and FRP 5%) the new rate of inflationary minor saving is seen to come at the rate of ₹ 11, 572/- per annum. Replacing 20 percent (RCA 10 percent + FRP 10 percent), the rate again comes down to the rate of (₹ 11442) and when the replacement is at 30 percent (RCA 15 percent + FRP 15 percent), the rate takes the value of (Rs. 11312/-). This trend means that the higher the quantity of the other materials will be filled in, the cheaper will be the total sum per cubic meter because the natural aggregate will be used less, which is more costly contrary to recycled materials. The relative change of cost on each level is however quite moderate, and it implies that despite being able to guess economic advantages, they are more appreciated at the big substitution rates (Fig 5).

6. Practical Recommendations

The experiment is verifying that the insertion of Recycled Concrete Aggregate (RCA) and Fiber-Reinforced Plastic (FRP) waste in concrete mixes can be an important component in the sustainable measures of the construction industry and it would not create any such implications in essential structural provisions offered by concrete, unless the percentage of substitution is moderated. In structural use, the best replacement is 10-20 percent (RCA and FRP together), strength in compression is good, exceeding 26.65 N/mm2, the standard grade of road construction MP is not lower than M 25, and the service life (water absorption, resistance to acids) does not exceed the allowable threshold; tests are within acceptable limits of IS, ASTM. Should a reduction in compressive strength below 25 N/mm2 be desired, outside this range, at an extent of 30 percent replacement, one may only utilize compression strength in non-load-bearing concerns like pavements, partition walls as well as footpaths. Confidence test showed that moderate replacements (10-20%) show a similar resistance to the conventional concrete and can be applied to constructions that may have medium aggressiveness of environment. But in the case of severe chemical exposures or high entry statistic members, the replacement percentage should not exceed 20 in order to preserve the standards of serviceability and safety.

In economic assessment, there is a progressive decrease in cost with a maximum of 3.3 percent savings at the 30 percent replacement level, mainly because of low costs of both natural aggregate usage and wastes management. Although the structural performance limits the level of use to a maximum of 20 percent in the structural elements where the burden is really high, the level of replacements can be increased in non-structural or temporary works where the principles of circular economy will be fulfilled. The ideals to assure workability and quality are also practical like water-cement ratio of 0.45 and below, superplasticizers, presoaked RCA to manage absorption, and dispersion of the FRP fabrics. Correct vibration during placing, longer curing duration (at least 14 days) as well as testing of the compressive strength in batches is important to achieve at all times. To start with, pilot projects of non-crucial parts begin operations, and subsequently, increase to structural ones, as actual results are proved. Finally, the creation of common RCA-FRP mix design guidelines and life cycle cost analysis (LCCA) will help promote the commercial use of the process in the industry where sustainable concrete will become a feasible alternative to everyday construction.

7. RESULT AND DISCUSSIONS

7.1 Compressive Strength and Structural Suitability

Analysis of the compressive strength indicated the definite tendency of the strength to decrease with the increasing content of the RCA and the FRP at the early age or later ages. After 7 days, the control mix had a strength of 22.74 N/mm2, giving 19.21 N/mm2, 18.17 N/mm2, and 16.16 N/mm 2 strengths of the 10, 20, and 30 percent replacements respectively, implying an absolute loss of up to 28.9 percent of the early-age strength to the highest replacement percentage. The same behavior was observed with the 28 days results, the control mix achieved 31.15 N/mm2 which is more than the requirements of the M25 grades, and 10% mix and 20% mix have a slight decrease in strength (6.6% and 14.4% respectively), but still conform to structural standards. However, the 30 percent mix attained 24.36 N/mm2 which is below the required compliance set in the IS 456:2000. The results indicate that partial substitution by 20 percent does not affect the structural capability of the load-bearing components, whereas the proportionate substitutions break the strength because of the porous nature of RCA which causes clustering of the fibers to form holes and break it down as a result of the FRP.

7.2 Durability Performance and Environmental Resistance

The tests of durability by water absorption and acid resistance also matched the expectations that RCA and FRP inclusion do have slight effects on porosity but still under acceptable levels. The water absorption was good (within IS 456 limits of 5%), rising only to 3.03 percent in 30 %, and the water absorption of 2.40 percent in the control was highly satisfactory. An exposure to acid decreased the strength of all mixes by 3-16%, control mix by 26.65 N/mm2 and 30% replacement mix decreased to 22.33 N/mm2. It is worth noting that 10-20% replacement mixes proved to be quite durable as observed in standard concrete; it is attributed to the fact that FRP fibers minimize spread of cracks during chemicals attack. These findings indicate that concrete reinforcement using RCA-FRP could be used in place of a structural component in a moderately hostile environment and the percentage above 20 is only recommended in non-structural activities so as to prevent durability issues.

8. CONCLUSION

Through experimental study, it was able to enable the possibility of using Recycled Concrete Aggregate (RCA) and Fiber Reinforced Plastic (FRP) as the partial replacements of natural coarse aggregates in M25 grade concrete to achieve the goal of sustainability without necessarily deteriorating the structural performance. The investigation led to the following important findings:

Mechanical Properties:

- The mix with zero percent replacement (The control mix or the one with no replacement) attained the maximum compressive strength of 31.15 N/mm^2 at 28 days.
- Replacement with up to 20% (RCA 10% + FRP 10%) retained a compressive strength of 26.65 N/mm^2 above the required 26.65 N/mm^2 of compressive strength in IS 456:2000 of concrete of grade M25.

- At 30% replacement, the strength fell below the target, suggesting its limitation for structural applications but suitability for non-structural components.

Durability Performance:

- There was relatively a slight increase of water absorption of 2.40% (control) to 3.03 % (30% replacement) which was within the permissible limit of 5% as stated by IS.
- Acid resistance tests showed loss in strength of up to 16.2 percent when exposed to 30 percent replacement by weight of H_2SO_4, but mixes up to 20 percent could be found durable in the moderate conditions of the environment.

Economic Feasibility:

- The cost of concrete decreased with an increase in the quantity of the replacement and it saved up to 3.3 at 30 percent of replacement compared to the normal concrete.
- The combination of 10- 20 percent substitution is most preferable due to its low costs and good mechanical properties. This renders them helpful to large projects.

Sustainability Benefits:

- Adding RCA and FRP promotes recycling of waste, reduces the quantity of wastes that are deposited in landfills and promotes circular economy activities.
- Both of these reduce the use of natural aggregates and have a reduction in the carbon footprint, which is in accordance with world sustainability standards.

Practical Implications

- Recommended Replacement Level: At most, 20 percent of structural uses should be made to ensure that it achieves the measures of strength and durability.
- 30% Replacement: It is good in non-structural applications such as paving blocks, footpaths and boundary walls where lower strengths are acceptable.

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