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Strength and Microstructural Behavior of Sustainable Concrete with Varied Proportions of Recycled Fine Aggregate from Construction and Demolition Waste

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ABSTRACT

Recycled fine aggregates (RFAs) encompass inorganic particles derived from the crushing of building and demolition waste, constituting an environmentally sustainable source for the concrete industry. This study explores the integration of construction and demolition (C&D) waste-based RFAs in concrete, aiming to reduce carbon emissions and promote eco-friendly construction practices. The RFAs, obtained from aging concrete structures, contribute fines to the concrete mixture, and their viability is assessed in this research. The investigation encompasses strength and microstructural analyses of RFA-based concrete blends with varying replacement percentages (20%, 40%, 60%, 80%, and 100%). The comprehensive evaluation spans 7 and 28 days of water curing, with particularly promising outcomes observed up to a 40% replacement threshold. The optimal performance is identified at the 40% RFA replacement, justifying the applicability of RFAs as an alternative fine aggregate. Microstructural studies conducted through a secondary electron microscope (SEM) specifically for the 40% RFA replacement substantiate the particle packing effect and corroborate the experimental findings. The findings underscore the sustainable potential of incorporating RFAs in concrete formulations, offering a pathway toward environmentally conscious and resilient concrete structures.

1. INTRODUCTION

In recent years, global environmental concerns have escalated, with the greenhouse effect, primarily driven by CO_2 emissions, standing out as a prominent issue. Cement production alone contributes approximately 7% to global carbon dioxide emissions. Mitigating the environmental impact and reducing CO_2 emissions necessitate exploring alternatives to traditional cementitious materials [1, 2]. Sand and gravel, constituting 60 to 80% of concrete volume, represent major aggregates. Recycling building and demolition debris as aggregate substitutes not only mitigates environmental impacts but also preserves finite natural resources, offering a sustainable solution [3].

The aggregate demand has led to rampant illegal quarrying, depleting natural resources and causing environmental harm. Utilizing recycled fine aggregate (RFA) and recycled coarse aggregate (RCA) in concrete has demonstrated positive effects on strength properties [4]. The construction industry generates significant construction and demolition (C&D) waste during building demolitions, contributing to global waste issues. C&D waste includes materials like wood, concrete, bricks, metal, masonry, sand, gravel, and soil. Recycling or reusing these materials is crucial for reducing carbon footprints and waste residuals [5, 6].

RCA, derived from C&D waste, serves as a valuable source of additional construction materials and supports structural use [7, 8], while RFA, obtained by crushing inorganic particles from building and demolition waste, is a critical component. The characteristics of RCA are influenced by the amount and quality of adhered mortar. Recycling waste concrete rather than depositing it in landfills can reduce environmental impact by up to 15%. However, achieving workability in fine RCA-based concrete mixes requires more water than their coarse RCA counterparts [9]. Moreover, RFA presents a superior interfacial transition zone (ITZ) and finer powder material [10]. Workability in concrete with RFA content exceeding 20% often necessitates pre-soaking the aggregates [11]. Regardless of RFA content, optimal fluid increases permeation and other mechanical characteristics in RFA mortar [12].

Numerous studies have explored various types of RFA-based concrete [13-15]. Given the variability of C&D waste across locations, a detailed investigation into C&D waste-based RFA is essential. This research examines the compressive strength, slump test, and split tensile strength of concrete with varying percentages of recycled fine aggregate (from 0% to 100%, in 20% intervals) without chemical admixtures (plasticizers/superplasticizers). SEM analysis was conducted on the optimal concrete mix to investigate microstructural aspects. The primary objective is to ascertain the optimum utilization of C&D waste-based RFA in concrete and explore its potential as an alternative fine aggregate.

2. EXPERIMENTAL PROGRAM

Mix proportions featuring six different replacement ratios of recycled fine aggregate (RFA) were utilized to examine the strength behavior of concrete. Additionally, the behavior of RFA-based concrete without chemical admixtures (plasticizers/superplasticizers) was assessed.

2.1 Materials

Cement of 53 grade confirming to IS 4031-1988 [16] was used as binder. The chemical composition of cement is depicted in Table 1. RFA was collected from C&D waste plant, Bangalore. The water absorption of RFA was 6.5% and the fineness modulus was 3.18. Crushed stone sand which is used as fine aggregate was acquired from the local quarry. A coarse aggregate of 20mm confirming IS 383: 2016 [17] was used. Potable water was utilized for the curing and mixing of concrete.

Table 1. Chemical composition of cement

Sl. No.	Characteristics	(% wt)
1	Silica	18.6
2	Aluminum oxide	3.77
3	Iron oxide	4.03
4	Calcium oxide	66.33
5	Magnesium oxide	2.13
6	Potassium oxide	0.46
7	Sulphuric anhydride	2.67
9	Alkali oxide	0.05
10	Loss of ignition	0.64

2.2 Mix proportion

Crushed stone sand was replaced with RFA from 0% to 100% with an interval of 20%. A total of 6 mix combinations were made without chemical admixtures (plasticizers/superplasticizers) as shown in Table 2. To check the workability of concrete, slump cone test was performed as per IS:1199-1999 [18].

Table 2. Mixture proportion (Kg/m^3)

Proportion%	Water	Cement	Fine Aggregate	Recycled Fine Aggregate	Coarse Aggregate
0	191.6	383.2	785.7	0	1075.74
20	191.6	383.2	628.56	157.14	1075.74
40	191.6	383.2	471.42	314.28	1075.74
60	191.6	383.2	314.28	471.42	1075.74
80	191.6	383.2	157.14	628.56	1075.74
100	191.6	383.2	0	785.7	1075.74

2.3 Tests on fresh concrete

The slump cone test was executed to evaluate the fresh properties of concrete with and without RFA. Many research findings focused on the addition of superplasticizers. So the fresh behavior of RFA-based concrete without superplasticizers was analyzed. The medium slump was observed up to 40% replacement of recycled fine aggregate, beyond that slump range was found to be low. The cause for the decrease in a slump with increasing RFA is mostly due to greater water absorption and the absence of chemical admixtures. Concrete made without chemical admixtures makes concrete economical when compared to concrete made with chemical admixtures (plasticizers/superplasticizers).

2.4 Tests on hardened concrete

To evaluate the hardened properties of concrete, compressive and split tensile strength test were conducted for specimens sized 150 × 150 × 150 mm (cubes) and 150 × 300 mm (cylinders), respectively. The compressive tests were conducted according to IS: 516-1959 (Reaffirmed 2021) [19]. After 7 days and 28days of curing, compressive strength test were performed as shown in Figure 1. The split tensile strength test was carried out on the compression testing machine as shown in Figure 2.

Figure 1. Compressive strength test

Figure 2. Split tensile strength test

3. RESULTS AND DISCUSSION

3.1 Compressive strength

Figure 3 depicts the results of compressive strength of concrete made with and without RFA. It's observed that after 7 and 28 days of curing increase in strength was found up to 40% RFA-based concrete, and incorporation of 60%, 80%, and 100% showed a decrease in strength. The result emphasized evidently that 40% RFA showed optimum strength to other mixes. Higher RFA content gave a deleterious effect on hardened concrete. Concrete containing more RFA tends to have a weak ITZ, which may be due to the nature of RFA and porosity [20, 21]. Addition of RFA more than 40% results in poor particle packing density. When comparing the percentage of strength improvement between control concrete and 40% RFA-based concrete at the age of 28 days is found to be 7%. The reduction of strength for higher volume RFA-based concrete is also due to shrinkage and reaction between old and new materials. The curing time plays an essential role in deciding the strength properties of concrete with RFA. The inclusion of excess water to achieve workability is the reason for low strength development for concrete made up of high volume RFA. The behavior of RFA in ordinary concrete can be easily optimized, nevertheless, it varies in special concrete [22, 23]. The enhanced cohesion between particles at up to 40% RFA replacement may contribute to improved compressive strength; indeed, RFA at levels up to 40% has been shown to enhance the hardened properties of concrete more than other mixes. Similarly, some researchers have suggested that the presence of unhydrated cement paste on the surface of RFA-based concrete aggregates could cause the cement to hydrate upon contact with water. This reaction could improve the cohesiveness of the particles, thereby increasing compressive strength [24].

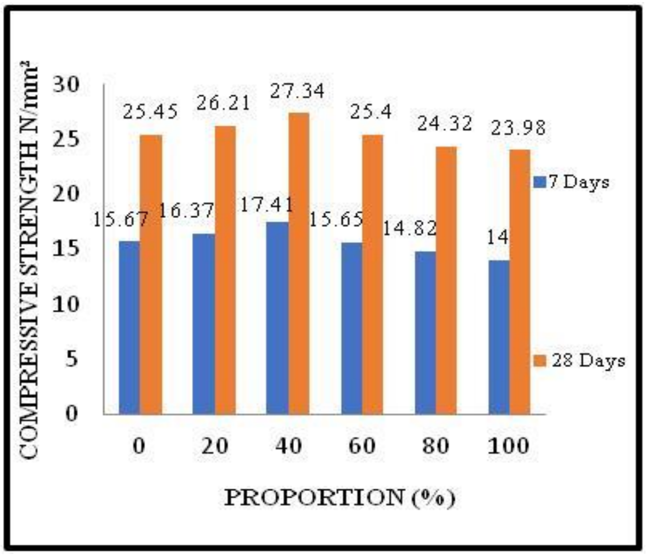

Figure 3. Compressive strength of RFA based concrete

3.2 Split tensile strength

The results for 7 and 28 days curing are depicted in Figure 4. The result pattern was moreover comparable to that of compressive strength. Specimen made up of 40% RFA showed good split tensile strength than other mixes, this is due to the surface texture (rough), size, and angular shape of RFA. Concrete made up of 20% and 40% RFA showed a split tensile value of 3.59 & 3.89 respectively at 28 days of curing. When comparing the control concrete and 40% RFA-based concrete, the increase in the percentage of splitting tensile strength is 12%. Strength loss was observed for addition of 60%, 80%, and 100% RFA. Similar types of results were reported by various researchers [25, 26]. Typical experiments were conducted for self-compacting concrete [27], Geopolymer concrete [28, 29] made up of different materials the result values are in range more over similar to the present work. Low volume RFA-based concrete showed good bonding between the materials thus resulting in enhanced split tensile strength. The reason for strength loss in high volume RFA may be due to the old mortar. 40% RFA-based concrete has a strong ITZ, it's also justified by SEM Images, the smoother transition between the RFA and other materials is the reason for optimum split tensile strength.

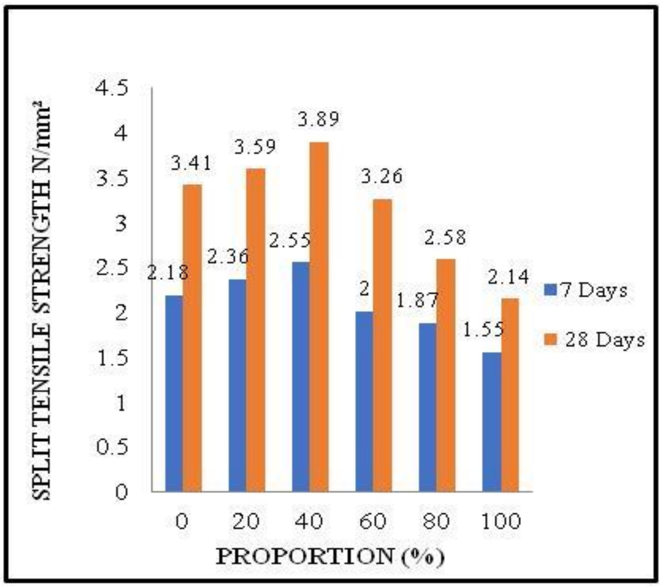

Figure 4. Split tensile strength of RFA based concrete

3.3 Microstructural behaviour

SEM analysis was performed on control concrete (Figure 5) and 40% RFA-based concrete (Figure 6). Observation of SEM image of control concrete confirms the presence of slight pores when compared to 40% RFA-based concrete. A weak ITZ was identified. Some unreacted particles were found, which may be the reason for less bonding and uncompactness. The clustered ITZ found in 40% RFA-based concrete is mainly due to particle size packing which in turn made it more water resistant than control concrete. The size and shape of RFA enhance the bonding between the particles. Some researchers reviewed the behaviour of different fine aggregates, depending on the properties, the microstructural behaviour of concrete varies [30]. Minor cracks were absorbed in the control concrete creating a weak link. Higher magnification identifies the micro cracks, nevertheless, good compactness was observed in 40% RFA-based concrete. The non-porous nature of 40% RFA-based concrete is one of the reasons for elevated compressive strength.

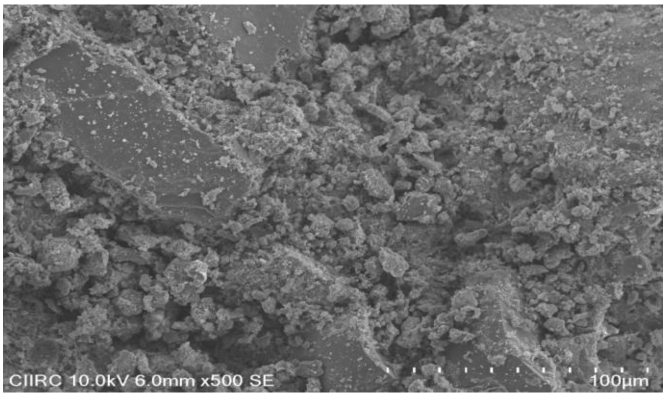

Figure 5. SEM image of control concrete

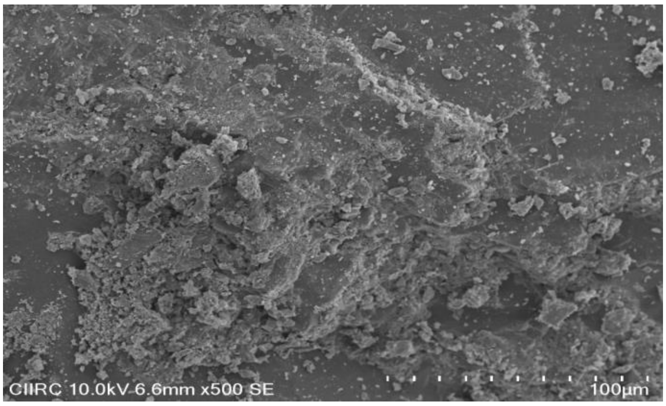

Figure 6. SEM image of 40% recycled aggregate concrete

4. CONCLUSION

This study investigated how the RFA replacement ratio affected the compressive and splitting tensile characteristics. From the experimental findings, the following conclusions are made.

- The workability of concrete declines as the proportion of recycled fine aggregate rises and a medium slump was observed in concrete mixes containing up to 40% RFA
- The compressive strength of concrete made using RFA at the age of 28 days ranged from 23MPa to 28MPa.
- The percentage increase of compressive strength for incorporation of 20% and 40% RFA was 3 percent and 7 percent, respectively when compared with reference mix.
- The split tensile strength of concrete made up of 40% RFA showed highest result of 3.89MPa.
- An optimum mix combination is achieved for the replacement of 40% recycled fine aggregate.
- Using recycled fine aggregate (C&D) is eco friendly and can be partially replaced up to 40%. This optimum percentage of C&D based RFA can be a good support for sustainable construction.

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NOMENCLATURE

RFA	Recylled Fine Aggregate
C&D	Construction and demolition
SEM	Scanning Electron Microscope