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Study on the mechanical property, water absorption, and acid resisitance of steel and polypropylene hybrid fiber reinforced recycled aggregate concrete

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ABSTRACT

This study aims to develop a sustainable solution in the construction industry by incorporating recycled aggregate (RA) into concrete, partially replacing natural gravel aggregate, and enhancing the strength of RA concrete through the addition of hybrid s The study investigates the effect of steel and polypropylene hybrid s on the mechanical and durability properties of recycled aggregate concrete (RAC). The research was carried out in three phases/mixes. The first mix is with different proportions of recycled aggregate (25% and 50%). The second mix is recycled aggregate concrete with only macro-steel , and the third mix is recycled aggregate concrete with different proportions of macro-steel and micro-polypropylene . Mechanical and durability properties were investigated in all three types of concrete mixes and compared with the control mix. The study concluded that the mechanical properties of hybrid fiber reinforced recycled aggregate concrete (HFRRAC) are dependent on the amount of recycled aggregate, proportions, and type. The macro-steel fibers with high elasticity modulus and stiffness improve the concrete´s strength and toughness. The increase in content affects the workability of -reinforced concrete. Synthetic microfibers with excellent ductility and dispersion improve concrete's mechanical properties and durability. Synthetic microfibers when used along with macro-steel improve both mechanical properties and durability characteristics.

1 Introduction

Urbanisation results in the construction of numerous new buildings and the demolition of old ones, leading to a significant build-up of construction and demolition waste [1]. Utilizing such waste concrete material into the concrete mainly reduces the consumption of natural aggregate and reduces land pollution. Replacing the coarse gravel aggregates which are the major ingredient in the concrete, with recycled aggregate (RA), may lead to a sustainable concrete solution [2]. Recycled aggregates, primarily used in the construction of non-structural members and for foundation filling, are often considered inferior to gravel aggregate. To change this idea, a lot of research is being carried out using RA, and investigations are being carried out to study the mechanical and durability properties of such recycled aggregate concrete (RAC) [3]. Researchers have reported that RA influences the major strength properties of concrete, exhibiting increased peak strain and a decrease in the modulus of elasticity under compression load [4]. Cement matrix, which is attached to the old aggregates, has an influence on the strength of concrete [5]. Thus, the proportions, aggregate type, amount of impurity, and other parameters influence the behaviour of recycled aggregate concrete.

To enhance the properties of recycled aggregate concrete, different types of fibers are added to the concrete to improve its strength, fracture behavior, and impact resistance [6]. The addition of macro-steel fibers in concrete improves the tensile property of concrete and the post-cracking behaviour [7]. The macro-steel fiber plays a major role after the appearance of the first crack in concrete and prolongs the ultimate failure of the structure [8]. The volume fraction, length of steel , and pattern of steel influence the performance of concrete [9], [10], [11], [12], and [13]. Studies seem to suggest that the compressive strength of macro-

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steel FRC increases by up to 10% when compared to plain concrete. Furthermore, the failure mode of macro-steel FRC transitions from brittle to ductile, resulting in a significant improvement in the post-cracking response [14]. These days, the light weight, chemical resistance, and high strength-to-weight ratio of micro-polypropylene fibers make them a popular choice for microfiber reinforcement. Micro-polypropylene fibers also improve the tensile property of plain concrete, showing high resistance to impact loads and better fracture behaviour [15], [16], and [17]. Today, concrete incorporates various natural fibers like jute, bamboo, banana, sisal, and caryota fibers [18] [19] [20] [21] as well as synthetic fibers like steel, polypropylene, plastic, glass, and basalt fibres [8] [22] [23] [24]. These fibers are used as monotype fibers or in combination as hybrid fibers. Popularly, macro-steel and micro-polypropylene fibers are used in combination as hybrid fibers. Macro steel fibers as a macro-scale reinforcement with a high Young's modulus are highly efficient in bridging the critical macro-cracks and improves the strength of concrete, and micro polypropylene fiber, as a micro-scale reinforcement, could reduce the plastic shrinkage cracks in the early age of concrete and enhance the post-cracking behavior [14], [25], and [26]. Based on the multiscale crack behaviour of concrete, it will be more advantageous to use both micro and macro fibers as hybrid reinforcement, which arrests cracks at micro and macro level. Hybrid fiber reinforcement also plays a major role in arresting the early stage shrinkage crack and post cracking behaviour of concrete [27].

As a result, blending two types of s in the concrete matrix appears to be more effective in crack arrest at multiple levels. The literature review revealed that numerous studies have examined the mechanical characteristics of recycled aggregate concrete reinforced with single and hybrid s. But an optimum proportion for hybrid fiber content is yet to be obtained. Therefore, the main objective of this research work is to study the mechanical behavior of recycled aggregate concrete with macro-steel fibers and micro polypropylene s. Mechanical properties such as compressive strength, tensile strength, and flexural properties, as well as durability properties such as water absorption and acid resistance, are to be studied in detail.

2 Experimental Investigation

2.1 Material characterization

The control concrete mix was prepared using ordinary Portland cement (specific gravity SG = 3.15 g/cm^3), lime stone gravel aggregate of size 10 mm used as coarse aggregate (CA), and recycled aggregate (RA) of size 18-20 mm used as a partial replacement for coarse aggregate. and river sand (SG = 2.74 g/cm^3) used as fine aggregate. To produce hybrid fiber reinforced recycled aggregate concrete, macro steel and micro polypropylene fiber were used in different proportions in addition to the above ingredients. The scanning electron microscope (SEM) image showing the detailed structure of macro-steel and micro-polypropylene is shown in Figure 1. The micro-polypropylene and macro-steel used in the present experimental investigation are shown in Figure 2. The physical properties of macro steel s and micro-polypropylene are listed in Tables 1 and 2, respectively.

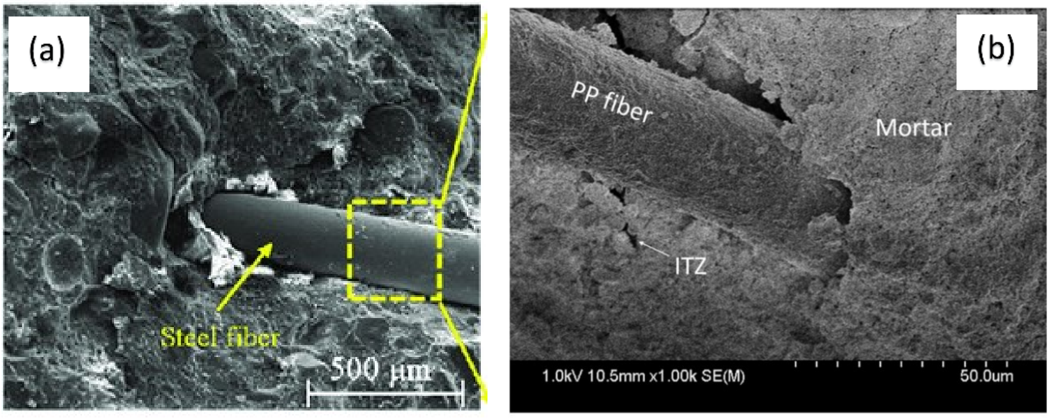


Figure 1. (a) SEM image: (a) Macro-steel fiber [28] (b) Micro-Polypropylene fiber [29] in concrete matrix

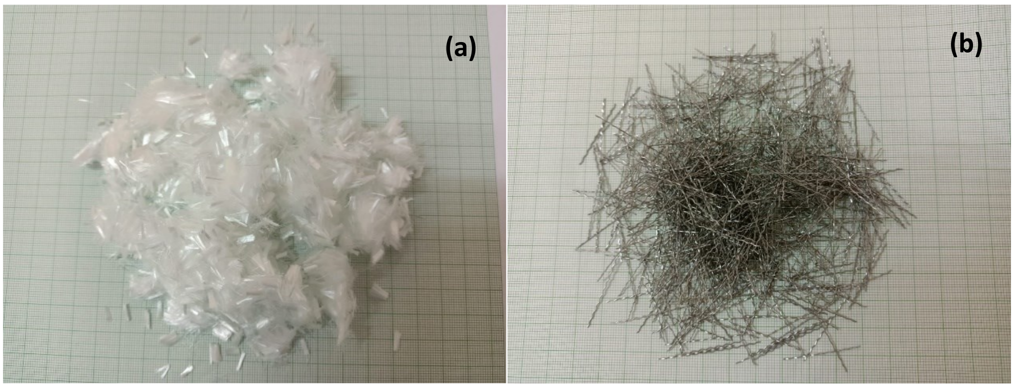


Figure 2. (a) Micro-Polypropylene fiber (b) Macro-Steel Fiber

Table 1. Physical property of macro steel fiber

Physical property	Range
Shape	Crimped steel fiber
Length (mm)	25
Diameter (mm)	0.5
Aspect Ratio (*l/d*)	50
Tensile Strength (MPa)	2650
Unit Weight (g/cm^3)	7.85
Coating	None
Elastic Modulus, (GPa)	200

Table 2. Physical property of micro-polypropylene fiber

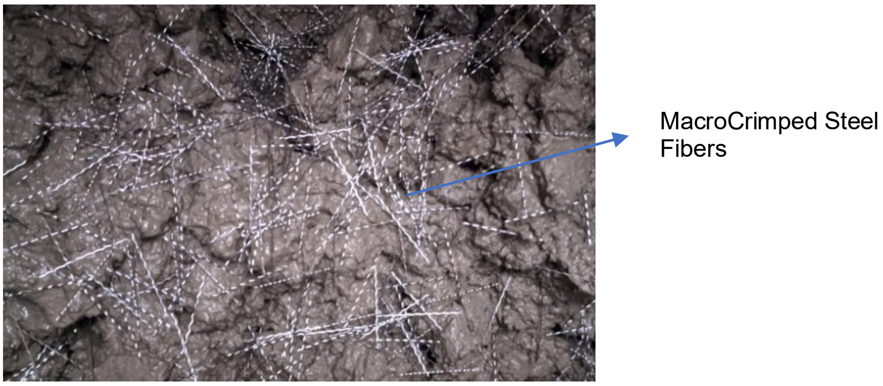
Physical property	Range
Raw material	100 % polypropylene
Type	monofilament
Length	4-5 mm
Diameter	30-40µm
Melting point	105±10°C
Softening point	95±10°C
Acid & alkaline resistance	Strong
Density	0.91 g/cm3
Colour	white
Water absorption	No
Specific Gravity	0.9
Youngs modulus	3.45 ×10^{3}Mpa
Tensile Strength	551 Mpa

2.2 Mix proportions and specimen ID

The concrete ingredients for the control mix, namely the cement, sand, coarse aggregate, water, and plasticizer, were mixed in the proportion of 1:1.64:1.72: 0.32: 0.01. The mix for concrete mortar cubes was done using a concrete mixer. Normal concrete cement of 19.8 kg fine aggregate of 30.15 kg, and coarse aggregate of 49.14 kg were filled in the mixer. We mixed the dry mixture for approximately one minute. After slowly adding water to the mixer and mixing it for two minutes, we cast the specimens. Fibers were added to the fresh concrete mix, and the concrete was mixed for another minute. Figures 3(a) and 3(b) show the addition of macro-crimped steel and micro-Polypropylene s, respectively. A total of 3 cubes (150 × 150 × 150 mm), 3 cylinders (150 × 300mm) and 3 beams (150 × 150 × 750 mm) were cast for each mix. For the preparation of hybrid fiber-reinforced recycled aggregate concrete, cement, fine, and coarse aggregates are added to the mixer. We added water to the mixture after mixing for 2 minutes. After allowing it to mix for 2 minutes, macro-steel and micro-polypropylene fiber were added to it. Table 3 lists the mix proportions.

2.3 Testing of specimens

According to IS 516:1959, a compression test was carried out on standard 150 mm x 150 mm x 150 mm cube specimens. All the cubes were tested in a surface dried condition, and for each mix combination, three cubes were tested at the age of 28 days using a compression testing machine of 1000 kN capacity. The loading was continued until the specimen reached its ultimate load. The load was applied without shock at a rate of 1.2 kN/m^2. In accordance with IS 516:1959, we conducted a tensile test on a 300 mm by 150 mm cylinder specimen after 28 days. The test was carried out on a universal testing machine of 2000 kN capacity. We calculated the tensile strength from the obtained load using the standard formula. For each mix, three cylinders were tested after 28 days of curing, and the mean value is reported. According to IS 516:1959, a flexural test was carried out on a beam specimen with dimensions of 500mm x 100mm x 100mm at the age of 28 days. A universal testing machine with a 2000 kN capacity conducted the test. Three-point loading was given to the specimens, and the flexural load was recorded at the time of failure. For each mix, three beams were tested after 28 days of curing, and the mean value was tabulated. Figure 4(a–d) displays the casted specimen and the mechanical testing of the specimen.



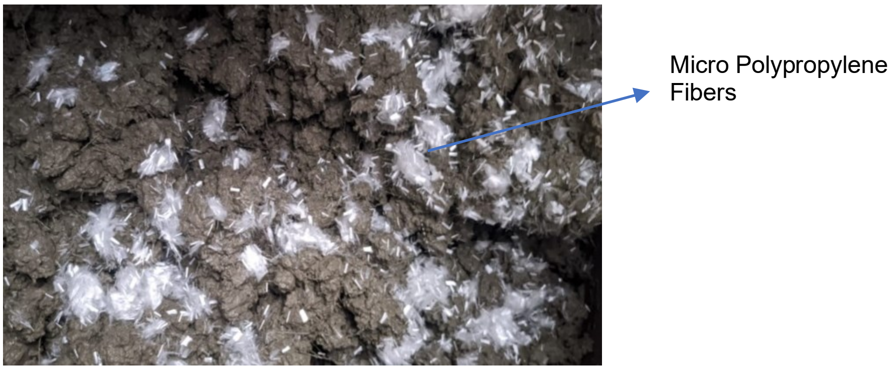


Figure 3. Mixing fibers in fresh concrete mix (a) macro-steel fiber (b) micro-polypropylene fiber

Table 3. Mix proportions

MIX	Cement (kg/m^3)	Recycled Aggregate (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Macro Steel fiber (kg/m^3)	Micro PP fiber (kg/m^3)
Normal mix	790	-	1966	1206	366	-	-
RCA 25	790	437	1474	1206	366	-	-
RCA 25% + SF 0.5%	790	437	1474	1206	366	70.4	-
RCA 25% + 0.75% SF + 0.25% PP	790	437	1474	1206	366	52.8	16
RCA 25% + 1% SF + 0.5%PP	790	437	1474	1206	366	140	70.4
RCA 50%	790	874	983	1206	366	-	-
RCA 50% + SF 0.5%	790	874	983	1206	366	70.4	-
RAC 50% + 0.75% SF + 0.25% PP	790	874	983	1206	366	52.8	16
RCA 50% + 1% SF + 0.5%PP	790	874	983	1206	366	140	70.4

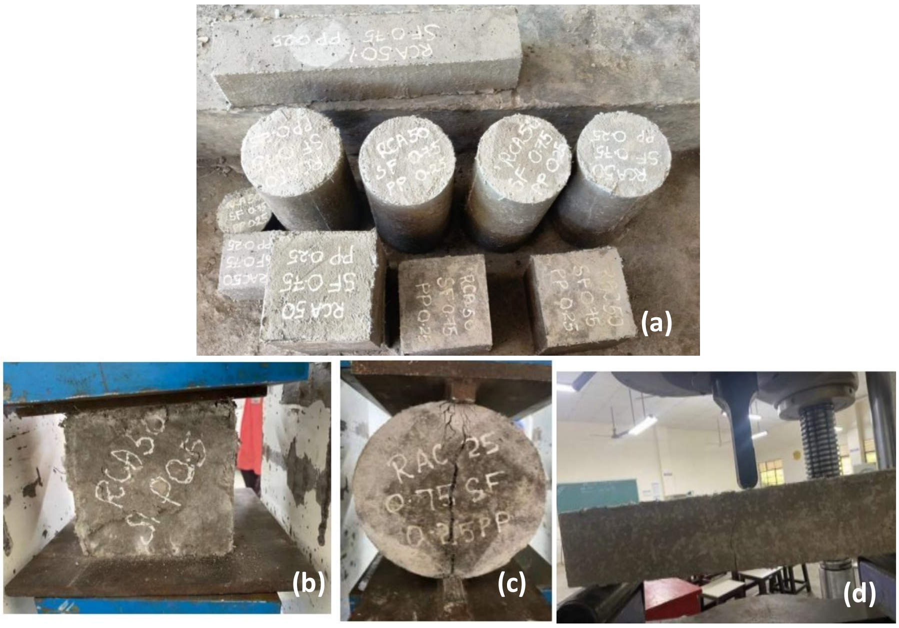


Figure 4(a). Cast specimens and (b-d) testing HFRAC specimens

2.4 Water absorption test

The water absorption test determines the water absorption rate (sorptivity) of both the outer and inner concrete surfaces. The test measures the increase in mass of concrete samples due to water absorption over time, with only one face of the specimen exposed to water. Concrete resistance against the ingress of aggressive ions is one of the major factors from the viewpoint of concrete durability. Water absorption behavior provides useful information about concrete porosity. It depicts the concrete's permeable pore volume as well as its pore connectivity. We dry the specimens in an oven for a specified time and temperature for the water absorption test, and then cool them in a desiccator. Immediately upon cooling, the specimens are weighed. The material is then immersed in water at agreed-upon conditions, often 23 °C for 24 hours or until equilibrium. Figure 5 illustrates the test arrangement for the water absorption test.

2.5 Acid Attack test

Concrete is susceptible to acid attack because of its alkaline nature. The components of the cement paste disintegrate when they come into contact with acids. The decomposition of the concrete depends on the porosity of the cement paste and the attention of the acid, and the solubility of the acid calcium salts (CaX_2). Insoluble calcium salts may percolate in the voids, slowing down the attack. Sulphuric acid interacts with the surface of the concrete, causing it to deteriorate. With the increase in environmental pollution, the rainwater has also become more acidic. Hence, there is a need to study the durability properties of concrete by exposing it to an acidic environment. We cast a 100 x 100 mm cube and cured it in a curing tank for 28 days. Concentrated sulphuric acid was diluted to 1N, and the mould was immersed in a tub containing the sulphuric acid solution shown in Figure 6(a). Initially, the dry weight of the mould was measured. After clearing the cube's surface with a metallic brush on the 3rd, 7th, and 14th days, we recorded the weight, as shown in Figure 6(b). Figure 6 (c-d) displays the cleaned cube specimen that underwent acid immersion for 3 days, 7 days, and 14 days. We tested the cubes under uniaxial compression after the 14th day and recorded the compressive load values.

Figure 5. Water absorption test arrangement for control Mix, RACand HYFRAC specimen

Figure 6(a). Cubes immersed in sulphuric acid (b) removing of loose materials with metal brush (c) Immersed cubes on 3rd day (d) Immersed cubes on 7th day (e) immersed cubes on 14th day

3 Results and Discussion

We conducted an experimental study to investigate the mechanical and durability properties of recycled aggregate concrete and hybrid fiber-reinforced recycled aggregate concrete. We observed mechanical properties such as compressive strength, flexural strength, and tensile strength, and Table 4 tabulates the results.

3.1 Workability of recycled aggregate concrete and hybrid fiber reinforced recycled aggregate concrete

A slump test is frequently used to measure the flow ability of concrete. The slump values dictate how easily the concrete flows and fits into the mould. Table 4 lists the recorded slump value for the current work. Figure 7 illustrates the variation in slump for the control mix using RAC and HFRRAC concrete mixes. Previous research work suggested that the slump of conventional concrete varies from 100 to 125 mm, while that of lightweight aggregate concrete ranges from 50 mm to 75 mm. The control mix recorded a slump value of 83 mm, which decreased as the amount of SF and PP in the concrete increased. With the addition of 25% and 50% of RAC, the slump value decreased to 80 mm, and 75 mm, respectively. This decrease in workability is due to the higher bulk density of RAC, which creates small pores in the cement matrix and occupies less volume in the concrete mix, making it more permeable and less flowable. The addition of macro-steel s hinders aggregate movement, reducing the workability of fresh concrete. The workability of RAC 50-SF 1-PP 0.5 concrete reduces from 80 mm to 68 mm with the addition of 1% macro-steel fiber. For HFRRAC, the workability drops even more to 76 mm and 72 mm when coarse aggregate is replaced by 25% and 0.75% macro-steel and 0.25% micro-PP are added, respectively. The accumulation of micro-PP fibers leads to the balling effect, which tends to reduce the workability of concrete.

Table 4. Slump and mechanical properties of RAC and HFRRAC

Specimen ID	Slump	Compressive Strength (N/mm^2)	Splitting Tensile Strength (N/mm^2)	Flexural Strength (N/mm^2)	Modulus of Elasticity (GPa)
Control Mix	83	30.2	2.12	4.3	27
RCA 25	80	31.33	1.98	4.1	27.56
RCA 50	78	34.23	2.55	4.45	27.9
RCA 25 – SF 0.5	77	33.78	3.11	4.75	28.2
RAC 25 – SF 0.75 – PP 0.25	76	21.56	2.83	3.45	27.92
RAC 25 – SF 1- PP 0.5	75	34.23	1.84	3.95	28.5
RAC 50 – SF 0.5	73	40.67	3.4	4.05	30
RAC 50 – SF 0.75 – PP 0.25	72	36.89	3.4	4.5	28.4
RAC 50 – SF 1 – PP 0.5	68	20.01	1.84	3.25	28.72

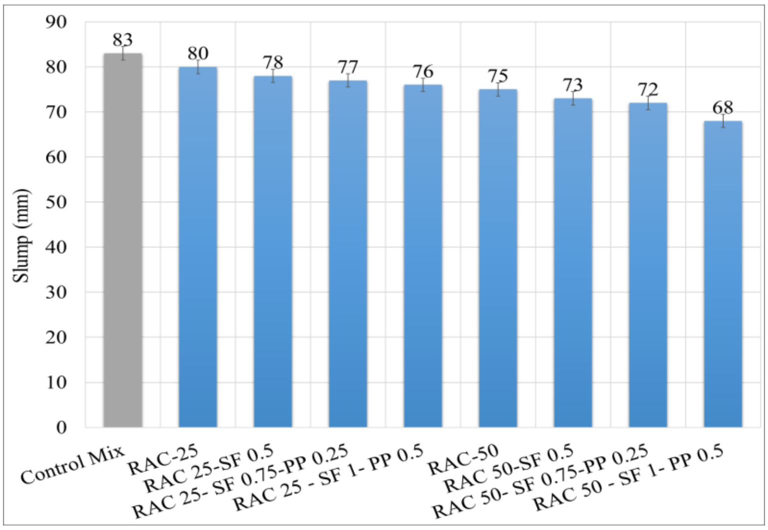


Figure 7. Variation of slump for control mix, RAC and HFRAC

3.2 Compressive strength of recycled aggregate concrete and hybrid fiber reinforced recycled aggregate concrete

The compression test was done on cubes of size 150mm x 150mm x 150mm specimens, which were dried in an oven after a curing period of 28 days. When compared to the control mix, the addition of 25% recycled aggregate leads to a minor increase in compressive strength (31.33 MPa). The addition of 0.5% macro-steel s increases the strength by 3 MPa in FRRAC specimens. In HYRAC, the addition of 0.5% PP s reduces the compressive strength to 21.56 MPa. An excess number of micro-fibers reduces the workability of concrete and increases the pores in the concrete specimen, which leads to a decrease in strength. While varying the composition of macro-steel s in concrete, it was noted that with an increase in the concentration of macro-steel s along with the addition of micro-PP fibers, the strength of the concrete decreased, and for the RAC 25-SF 1-PP 0.5 mix, a considerable drop in strength can be observed. However, the mix constituting RAC and steel fibers alone showed the maximum strength achieved after 28 days in the RAC 50 – SF 0.5 mix. Similarly, for a 50% replacement of aggregate with RAC, an increase in the SF composition alone resulted in an increase in strength for up to 0.5% SF. Beyond 0.5% SF, and the addition of micro-PP s slightly reduces the strength. The results conclude that the RAC 50-SF 0.5 mix is the most optimal mix for designing concrete that can withstand high compressive strength. Figure 8 illustrates the variation in compressive strength for the control mix, RAC, and hybrid -reinforced concrete. Despite the addition of excess microfibers reducing the strength, Figure 9 shows a wide range of cracks spreading throughout the entire specimen in the cube failure pattern. The poor compaction of the concrete mix with microfibers may be the cause of the strength reduction. Therefore, the micro-s help to disperse the cracks and prevent sudden failure of the concrete specimen.

3.3 Flexural strength of recycled aggregate concrete and hybrid fiber reinforced recycled aggregate concrete

Table 4 provides the flexural strengths of the control specimens, RAC, FRRAC, and HFRRAC. The control specimen's flexural strength was 4.3 MPa, which decreased by 4% for a 25% aggregate replacement with RAC. Flexural strength, like compression and splitting tensile strength, increases with the addition of SF and hybrid . For hybrid fiber, RAC 25-SF 1-PP 0.5 showed reduced flexural strength (3.4 MPa) which is like the previous test results. When 0.75% macro-steel and 0.25% micro-PP were added to the control mix (CM), the strength of the hybrid -reinforced mix went up by 9.5%. The addition of increases the post-peak toughness of the beam under flexural load. All the s embedded in the concrete matrix contribute to stress transfer until the specimen fails, a process that occurs once the s reach their ultimate capacity. For a 50% replacement of RAC, the flexural strength values range from 3.95 MPa, 4.05 MPa, 4.5

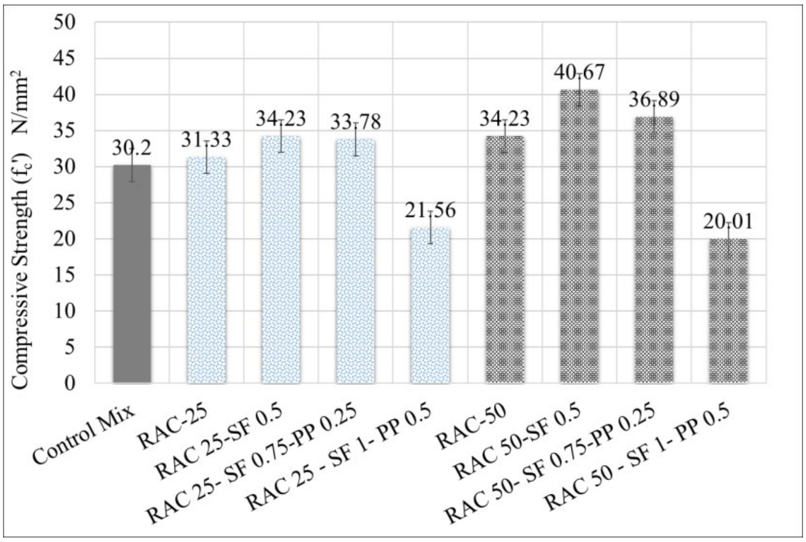


Figure 8. Compression strength of RAC and HFRRAC

Figure 9. Formation of micro cracks in hybrid fiber reinforced recycled aggregate concrete (a) 25% RAC & (b) 50% RAC

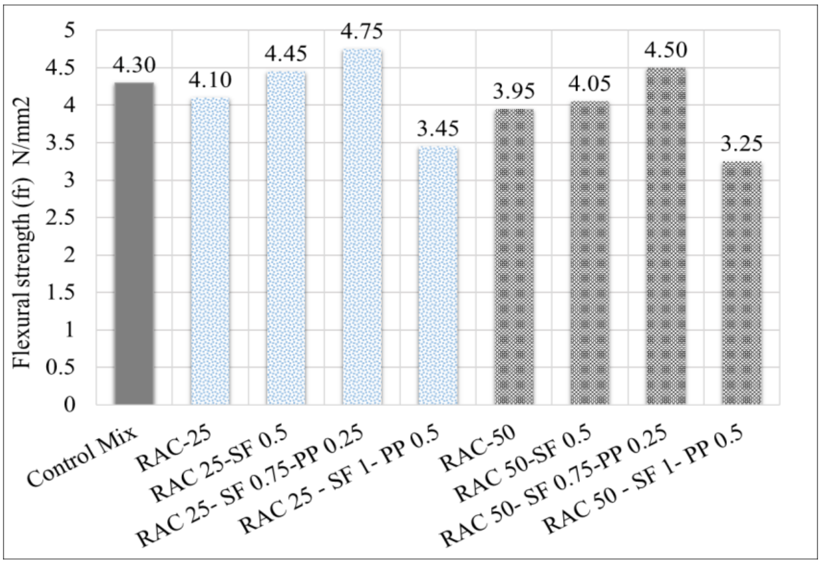


Figure 10. Flexural strength of RAC and HFRRAC

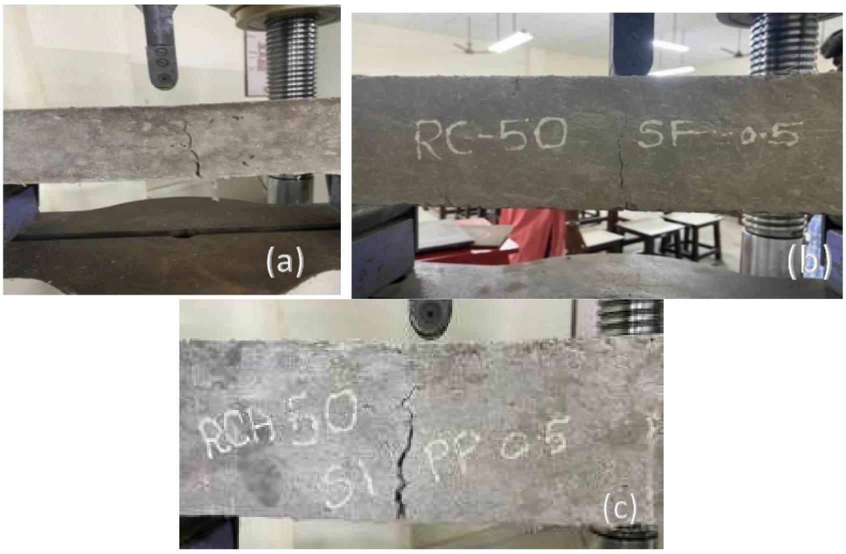


Figure 11 flexural test of (a) RAC (b) SFRAC, & (c) HFRRAC

MPa, and 3.25 MPa for RAC 50, RAC 50-SF 0.5, RAC 50-SF 0.75-PP 0.25, and RAC 50-SF 1-PP 0.5, respectively. Figure 10 illustrates the variation in flexural strength. The present flexural strength values agree well with the previous research findings. Figure 11 (a–c) displays the failure pattern for the control mix, FRRAC, and HFR RAC.for the control mix, FRRAC, and HFR RAC.

3.4 Modulus of elasticity of recycled aggregate concrete and hybrid fiber reinforced recycled aggregate concrete

Within the elastic region, the ratio of stress and corresponding strain measures the value of modulus of elasticity (MoE) of concrete. Since concrete is a brittle material, the addition of macro-steel s helps to improve the strength properties, mainly the compression, and flexural strength, thereby increasing the modulus of elasticity value. Figure 12 illustrates the variation in MoE between RAC and HFRRAC materials. For the control specimen, the MoE was 27 GPa, which slightly increased to 27.6 GPa with the addition of 25% RAC. The orientation of the macro-steel fibers helps to increase the concrete mix's modulus of elasticity. The addition of SF and PP leads to an increase in the modulus of elasticity (MoE), which is in line with the values for compression, tension, and flexural strength. When we replace 50% of the aggregate with recycled aggregate and 0.5% SF, the modulus of elasticity (MoE) increases to 30 GPa (RAC 50–SSF 0.5), indicating a 10% increase compared to the control mix. For the fourth series of specimens, namely the RAC 25-SF 1-PP 0.5, the MoE decreases to 27.9 GPa.RAC 50, RAC 50- SF 0.5, RAC 50-SF 0.75 – PP 0.25 and RAC 50 – SF 1 – PP 0.5 the MoE values were 28.5 GPa, 30 GPa, 28.4 GPa, and 28.7 GPa, respectively. The voids in the concrete mix decrease with the amount of SF and PP, which also increase the strength of the concrete and thereby the MoE value. Therefore, we can conclude that the addition of RAC, SF, and PP s reduces the strain in the concrete under the applied compression load, thereby increasing the modulus of elasticity. Figure 13 displays the specimen that failed the axial compression test.

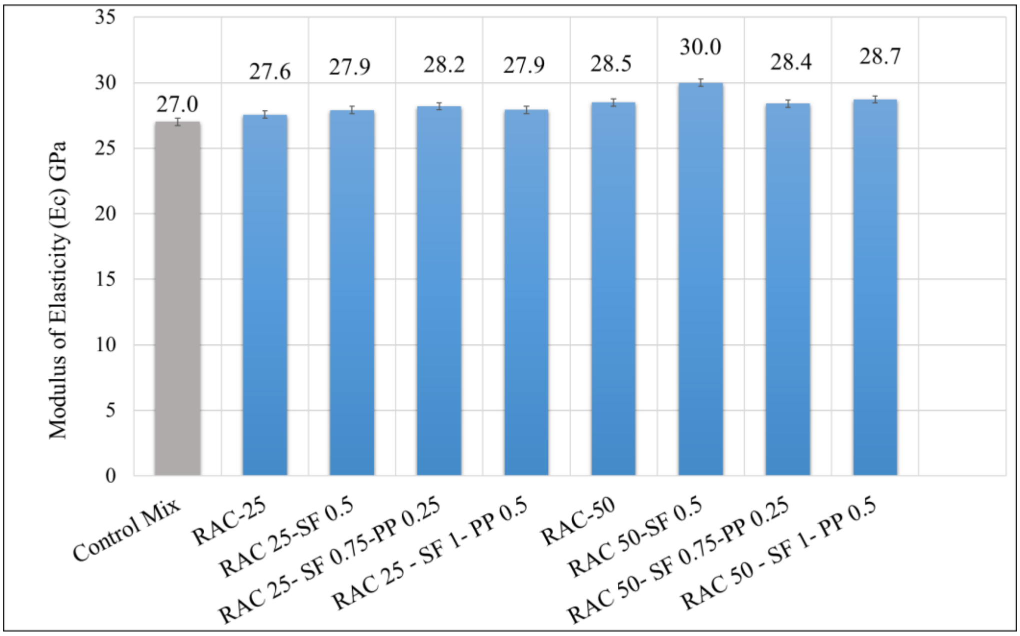


Figure 12. Modulus of elasticity of RAC, SFRAC and HFRRAC specimens

Figure 13. Tested specimen for Modulus of elasticity

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3.5 Water absorption of recycled aggregate concrete and hybrid fiber reinforced recycled aggregate concrete.

For the water absorption test, the specimens were dried in an oven for a specified time and temperature and then placed in a desiccator to cool. Immediately upon cooling, the dry weight of the specimen was recorded. The cylinder specimen was then partially immersed in water to allow capillary movement of water particles through the specimen. The weight of the specimen was measured at regular intervals until the saturation condition was reached. For the normal mix, the dry weight of the specimen was found to be 0.88 kg, and the weight after 30 minutes and 3 days was found to be 0.89 kg, and 0.91 kg, respectively, with an initial water absorption of 1.14% and a final water absorption of 3.41%. Increasing the amount of recycled aggregate in concrete leads to an increase in water absorption. The water absorption percentages after 30 minutes were 1.83%, and 1.82% for RAC 20, and RAC 50, respectively. For macro-steel -reinforced RAC, the water absorption percentage was 1.54% and 2.06% for RAC 25-05 SF. With the addition of hybrid s, the water absorption percentage increased with the increase in micro-PP content. We observed the highest water absorption value for RAC 25-1 SF + 0.55 PP, with an initial water absorption of 8.57% and a final absorption of 16.29%. An increase in the weight of the specimen after immersing it in water reflects that with the increase in RAC composition, the water absorption increases, which is due to the presence of old concrete particles adhering to the aggregate. Also, the PP s tend to increase the water absorption percentage, which is mainly due to the increase in porosity of the concrete specimen. Table 5 tabulates the water absorption test results. Figure 14 displays the initial water absorption and final after-absorption of RAC, SFRAC, and HFRRAC.

Table 5. Water absorption test result

Specimen ID	Dry weight of Specimen (kg)	Weight of specimen after 30 min (kg)	Weight of specimen after 3 days (kg)	Initial Water Absorption (30 min) %	Final water Absorption % (After 3 days)
Control mix	0.88	0.89	0.91	1.14	3.41
RCA-25	0.872	0.888	0.919	1.83	5.39
RCA-50	0.879	0.895	0.926	1.82	5.35
RCA-25-0.5SF	0.91	0.924	0.957	1.54	5.16
RCA-50-0.5SF	0.923	0.942	0.974	2.06	5.53
RAC-25-0.75SF-0.25PP	0.852	0.872	0.91	2.35	6.81
RAC-50-0.75SF-0.25PP	0.868	0.888	0.931	2.30	7.26
RAC-25-1SF-0.5PP	0.669	0.733	0.778	9.57	16.29
RAC-50-1SF-0.5PP	0.665	0.722	0.778	8.57	16.99

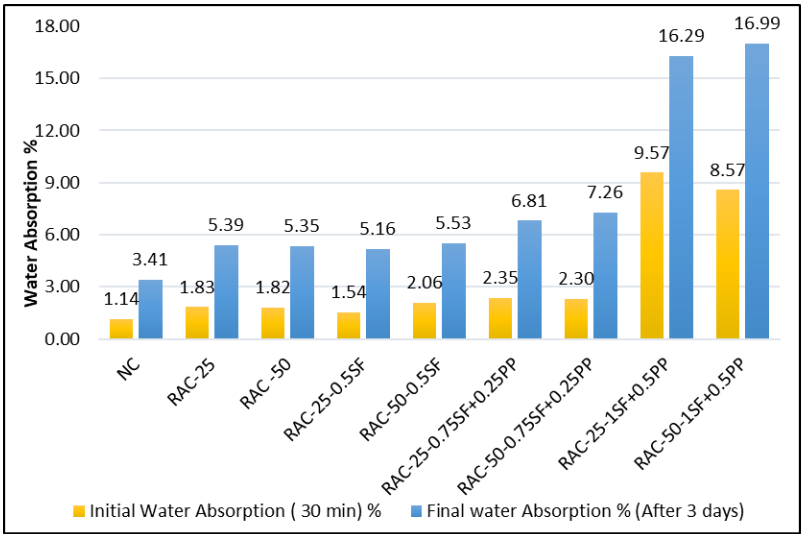

Figure 14. Water absorption percentages after 30 minutes and 3 hours RAC and HFRRAC specimens

3.6 Acid attack test

Acid resistance refers to a material or colour's ability to resist degradation upon exposure to acid. Durability tests of acid resistance of concrete were determined in terms of weight loss and residual compressive strength. We cast and cure concrete cubes for this test, noting their initial dry weight before conducting the acid resistance test. Next, we immerse the cubes in sulfuric acid for three days, remove them, give them a thorough rub, and note their weight after three days. The cubes are again immersed in the sulphuric acid for seven days. The weight of the cubes after seven days of acid attack is noted. The cubes are cleaned, rubbed, and again immersed in acid for 14 days, the weight of the cubes is noted. The comparative weight of the cubes after immersing in acid is noted on the third, the seventh and the fourteenth day to check the durability of the cubes. Table 6 tabulates the amount of weight loss in the concrete specimen following acid exposure. Compared to the control mix, the percentage weight loss for RAC was 3.42% and 7.57% for RAC 25 and RAC 50, respectively. With the addition of s, the weight loss due to acid attack increased slightly to 4.97 and 7.27 for RCA-25-0.5SF and RCA-50-0.5SF respectively. For hybrid - reinforced concrete, the weight was observed to be a maximum of 10.92% for RAC-50-1SF-0.5PP. Thus, the addition of s tends to slightly increase the pores in concrete and thereby increase the possibility of acid attack.

Figure 15 shows the surface of the specimen exposing the s after 7 and 14 days in an acid environment. After 14 days, the compressive strength of the cube specimen subjected to an acid environment was tested and tabulated in Table 7. Figure 16 shows the variation of strength after acid attack. The results showed that the macro-steel - reinforced specimen's strength was approximately 20 Mpa and 15 Mpa for 25% and 50% RAC replacement, respectively. For hybrid reinforcement, the strength was 24 MPa and 22 Mpa which is slightly lower when compared to control specimen. Thus, the addition of s tends to improve the strength properties of concrete both, in a normal as well as an acidic environment. But an increase in the micro content reduces the strength due to an increase in the porosity of the concrete specimen.

Table 6. Specimen weight loss after acid attack

Specimen	Dry weight of the cube (kg)	3rd day weight of the cube (kg)	7th day weight of the cube (kg)	14th day weight of the cube (kg)	Percentage weight loss after 14 days (%)
Control mix	2.484	2.46	2.43	2.40	3.38
RCA-25	2.340	2.32	2.30	2.26	3.42
RCA-50	2.337	2.31	2.25	2.16	7.57
RCA-25-0.5SF	2.336	2.30	2.26	2.22	4.97
RCA-50-0.5SF	2.448	2.41	2.36	2.27	7.27
RAC-25-0.75SF-0.25PP	2.450	2.42	2.39	2.35	4.08
RAC-50-0.75SF-0.25PP	2.563	2.53	2.47	2.35	8.31
RAC-25-1SF-0.5PP	2.287	2.263	2.20	2.17	5.12
RAC-50-1SF-0.5PP	2.391	2.37	2.26	2.13	10.92

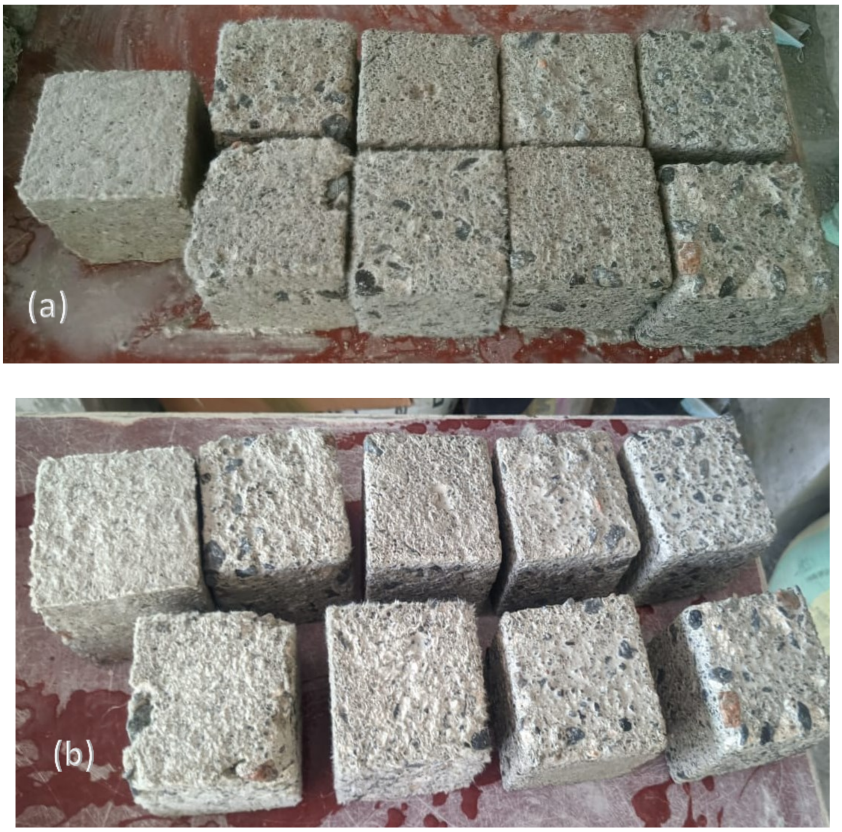

Figure 15. Acid attack specimen after (a) 7 days and (b) 14 days

Table 7. Acid attack test compressive strength

Specimen ID	Compressive strength (N/mm^2)
NC	27
RAC-25	13
RAC -50	23
RAC-25-0.5SF	20
RAC-50-0.5SF	15
RAC-25-0.75SF+0.25PP	24
RAC-50-0.75SF+0.25PP	22
RAC-25-1SF+0.5PP	5
RAC-50-1SF+0.5PP	6

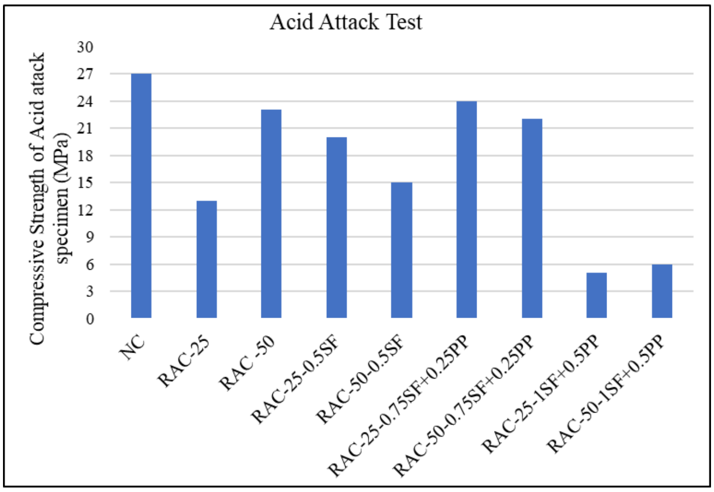

Figure 16. Compressive strength of RAC & HFRRAC specimen subjected to acid environment.

4 Conclusion

From the experimental investigation carried out to study the mechanical and durability properties of RAC and HFRRAC, the following conclusions can be derived:

- The control mix recorded a slump of 83 mm, which decreased as the percentage of RAC, SF, and PP increased. For the mixes RAC 25, RAC 25-SF 0.5, RAC 25-SF 0.25- PP 0.25, RAC 25- SF 1- PP 0.5, RAC 50, RAC 50- SF 0.5, RAC 50- SF 0.75 – PP 0.25 and RAC 50 – SF 1 – PP 0.5 the slump value decreases to 80mm, 78mm, 77mm, 76mm, 76mm, 75mm, 73mm, 72mm, 68mm.
- The RAC mix's compressive strength increased by up to 4% compared to the unreinforced mix (CM). The compressive strength of the HFRRAC increases and then decreases as the percentage of macro steel increases.
- The addition of RAC, SF, and PP s increases and decreases the flexural strength. For HFRRAC, the strength properties decrease as the percentage of macro-SF increases. The reduction in strength properties with the increase in the percentage of macro-SF is due to the orientation of SF fibers, bond between the aggregate and cement matrix.
- The modulus of elasticity value increases with the addition of RAC, macro-SF and micro-PP s. For HFRRAC, the strength properties increase as the percentage of macro-SF and micro-PP increases. The orientation of the aggregate, the bond between the aggregate and cement matrix, or the elongated shape of the aggregate all contribute to the increase in strength properties as the percentage of coconut shell increases.
- None of the tested specimens showed evidence of fracture in the recycled aggregate, demonstrating its unrestricted use as a replacement for conventional aggregate. Therefore, it can be concluded that RAC, macro-steel and micro-polypropylene can be effectively used as reinforcement in concrete to produce a sustainable concrete solution.

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