ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 13, NO. 1 (2012)
PAGES 55-77

STRENGTH AND PERMEABILITY CHARACTERISTICS OF FIBER REINFORCED HIGH PERFORMANCE CONCRETE WITH RECYCLED AGGREGATES

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Received: 10 November 2011; **Accepted:** 20 August 2011

ABSTRACT

Concrete is not an environmentally friendly material due to its destructive resource-consumption nature and severe environmental impact. However it is one of the major construction materials being utilized globally. For development, the concrete industry has to plan and implement the better use of recycled materials in concrete making. Even though the utilization of recycled aggregates in the concrete industry has been taking place for many years, the promotion of this recycled material as an alternative has never been easy in the industry. Though lot of research has been reported on RAC, very little information is available about the effect of using recycled aggregate in the production of Fiber Reinforced High Performance Concrete (FRHPC). This paper presents the results of experimentation conducted to evaluate the strength and permeability characteristics of FRHPC produced with recycled coarse and fine aggregates. Three types of fibers viz., steel, glass and poly propylene fibers are used in the production of FRHPC. Compressive, tensile, flexural and shear strengths of Fiber Reinforced High Performance Recycled Aggregate Concrete (FRHPRAC) have been evaluated from the experimentation. Chloride ion permeability has been determined as measure of permeability of FRHPRAC. The results of the study show that recycled coarse and fine aggregates can be successfully used in the production of fiber reinforced high performance concrete.

Keywords: High performance concrete; recycled aggregate; fiber reinforced concrete; chloride ion permeability; glass fibers; poly propylene fibers; steel fibers

1. INTRODUCTION

Concrete is the premier construction material used widely across the world in all types of engineering works, including infrastructure, low and high-rise buildings, defence installations and local/ domestic developments. It plays an important role in shaping our environment and sustainability of construction industry. Efforts to improve the properties

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of concrete are continuously being made by researchers which led to the development of fiber reinforced concrete, Ferro-cement concrete, slurry infiltrated fibrous concrete etc. In recent years, improvements in concrete properties have been achieved by the invention of High Performance Concrete (HPC). High performance concrete as it is well known can be designed to have higher workability, higher mechanical properties and greater resistance to chemical attack than those of traditional concrete [1]. In HPC, a substantial reduction in water-to-cement ratio is achieved through the use of super plasticizers. Further enhancements of some properties have been obtained through the addition of mineral micro fillers or mineral admixtures such as metakaolin, silica fume and fly ash. Poon et. al. related the mechanical and durability properties of high performance metakaolin and silica fume concretes to their microstructure characteristics [2]. They reported that metakaolin concrete has superior strength development and similar chloride resistance to silica fume concrete. Sun et al. presented the study on the influence of mineral admixtures on resistance to corrosion of steel bars in green high performance concrete [3]. The results showed that the addition of mineral admixtures reduced the pH values of the binder pastes in green high performance concrete. The addition of fibers to concrete has been shown to increase strength, ductility and fatigue strength of concrete. Fiber Reinforced High Performance Concrete (FRHPC) can be effectively used in RCC members subjected to extreme loading conditions such as seismic loading, blast loading and impact loading. It is generally accepted that the presence of fibers improves the performance of concrete in compression. The main functions of the fibers in members subjected to compression are to resist the opening of cracks due to micro-cracking, increase the ability of the composite to withstand loads, and to allow larger strains in the neighborhood of fibers. Shannag et al. studied the effect of using high performance steel fiber reinforced concrete in place of conventional concrete in the joint regions and reported that hooked steel fibers showed a significant increase in the maximum load carrying capacity [4]. Lim and Nawy investigated the mechanical characteristics of plain and steel fiber reinforced HPC under uni-axial and biaxial loading conditions and reported the better performance of the latter [5]. Ganesan et al. characterized the ultimate strength of steel fiber reinforced self compacting concrete in flexure [6]. Ganesan and Sekar investigated the effect of micro silica and steel fibers on the strength of HPC and reported that the addition of micro silica and steel fibers improve the strength of HPC [7]. Ganesan et al. studied the behavior of reinforced HPC members under flexure and reported that the reinforcement incorporation has positive effect on flexural strength of HPC [8]. Joost reported the progress in knowledge and provisions of new design codes for High Performance Fiber reinforced concrete [9]. Bandelj et. al investigated the free shrinkage characteristics of High Performance Steel Fiber reinforced concrete [10].

Recycled aggregates are produced from the re-processing of waste materials, the largest source being Construction and Demolition (C&D) waste. According to Commonwealth Scientific & Industrial Research Organization (CSIRO), C & D waste makes up to around 40% of the total waste each year (estimated around 14 million tons) posing severe disposal problems. The reuse of this construction and demolition waste in the form of recycled aggregate concrete (RAC) is viewed as an effective attempt to conserve the natural resources and preserving the environmental ecological balance. The research work carried out in the past on the use of recycled aggregates is mainly focused on issues related to the processing of C&D waste, mechanical properties, mix design and durability [11-15]. In fact suitability of coarse recycled aggregates for use in normal grade concretes for a large range of applications has been proven in a number of studies [16-17]. Studies concerning the structural behavior of recycled aggregate concrete structural elements are also reported in literature [18-22]. The seismic performance of RAC structural elements are also reported [23-24]**.** Though it is established that FRHPC is superior to ordinary concrete in many applications, very little research has been carried out on utilizing the recycled aggregates in the production of FRHPC. Many waste materials have been proven to be successfully utilized in the manufacturing of normal concrete Chandra [25]. However, there are only a few attempts to utilize recycled aggregates in the production of HPC due to the original defects of recycled aggregates Tam et,al [26]. Nevertheless, the utilization of recycled aggregates for HPC is still necessary, as HPC is becoming more and more widely used around the globe. Furthermore, the utilization of recycled aggregates in the production of FRHPC might at least lead to the concrete industry to embrace the concept of sustainable development in the near future. Accordingly, this paper will examine the strength and durability properties of Fiber Reinforced High Performance Concrete (FRHPC) which use recycled aggregates that have originated from demolished construction wastes. Experimental results conducted to establish the feasibility of using recycled coarse and fine aggregates in the production of Fiber Reinforced High Performance Recycled Aggregate Concrete (FRHPRAC) are presented. Three types of fibers viz., steel, glass and polypropylene fibers are used in the production of FRHPRAC. Compressive, tensile, flexural and shear strengths of Fiber Reinforced High Performance Recycled Aggregate Concrete (FRHPRAC) have been evaluated from the experimentation. Chloride ion permeability has been determined as measure of permeability of FRHPRAC.

2. RESEARCH SIGNIFICANCE

Though it is established that recycled aggregates can safely be used in the ordinary concrete, very little research is available on their utilization in the production of FRHPC. In the present investigation, the feasibility of using recycled coarse and fine aggregates in the production of FRHPC is being studied. Steel, glass and polypropylene fibers have been used in the production of FRHPRAC. Fibers were mixed in different volume fractions ranging from 0.5 to 1.25%. Important mechanical properties such as compressive, tensile, flexural and shear strengths of FRRAHPC have been determined from the experimentation. Rapid chloride permeability test was conducted to evaluate the permeability characteristics of FRHPRAC as a durability parameter. For comparison purposes, a reference concrete of M20 grade with natural aggregates was also prepared and tested for strength and permeability. This paper provides very useful information on both strength and durability of FRHPRAC produced with recycled coarse and fine aggregates.

3. EXPERIMENTAL PROGRAMME

3.1 Materials and mix proportions

3.1.1 Cement

Ordinary Portland cement of 53 grade with specific gravity 3.06 was used. The initial and final setting times were found as 40 minutes and 360 minutes respectively.

3.1.2 Natural fine aggregate

Locally available river sand passing through 4.75 mm IS. Sieve with a fineness modulus of 2.74, and water absorption in saturated surface dry (SSD) condition of 1.5% was used. The specific gravity of the sand is found to be 2.61.

3.1.3 Natural coarse aggregate

Crushed granite metal with 50% passing through 12.5mm and retained on 10mm sieve and 50% passing through 20mm and retained on 12.5mm sieve was used. Crushed granite aggregate available from local sources with a fineness modulus of 6.73, and water absorption of 0.72% in SSD condition has been used. The specific gravity of coarse aggregate is found to be 2.75. The maximum size of the coarse aggregate was 20mm.

3.1.4 Recycled aggregates

The recycled fine and coarse aggregate that were used have been obtained from the demolition waste of a sixty year old building in a thermal power station located in the vicinity. The R.C.C. demolition waste was processed in a crusher and then sieved. The fraction between 4.75 to 20mm was used as Recycled Coarse Aggregate (RCA) and the portion passing through 4.75mm sieve was used as Recycled Fine Aggregate (RFA). The specific gravity of RCA is 2.69 and the water absorption is 3.12% with a fineness modulus of 6.42. The specific gravity of RFA is 2.71 and the water absorption is 8.2% with a fineness modulus of 2.61

3.1.5 Water

Potable fresh water available from local sources free from deleterious materials was used for mixing and curing of all the mixes tried in this investigation.

3.1.6 Super plasticizer

The super plasticizer used in this experiment is SP 337. It is manufactured by FOSROC, Bangalore. It complies to IS: 9103 – 1999 standards.

3.1.7 Fibers

Three types of fibers were used in this investigation to produce three types of FRHPCs. Steel fibers of 1mm diameter and 100mm length with an aspect ratio of 100 were used. Glass fibers supplied by SAINT GOBAIN Company with a filament diameter of 14 microns and 12mm length with specific gravity of 2.68 were used. Polypropylene fibers manufactured by Reliance Industry with a commercial name ‘Recron-3S’ of length 12mm and diameter of 12 microns having a specific gravity of 1.36 were used.

3.1.8 Metakaolin

The mineral admixture Metakaolin is obtained from the 20 MICRON LIMITED company at Vadodara in Gujarat. The specific gravity of Metakaolin is 2.54. Twenty percent of cement is replaced with Metakaolin and is maintained constant for all HPC mixes. The properties of metakaolin are presented in Table 1.

Table 1: Properties of metakaolin

S. No	Property	Value
1	Specific gravity	2.54
2	Accelerated pozzolanic active index, % of control	89
3	Residue on 45µ sieve, %	1.31
4	Chemical analysis, %	
	Loss on ignition	0.70
	Silica (SiO_2)	52.24
	Iron oxide (Fe_2O_3)	0.60
	Aluminium (Al_2O_3)	43.18
	Calcium oxide (CaO)	1.03
	Magnesium oxide (MgO)	0.61

3.1.9 Types of concrete mixes

The main objective of this investigation is to study the feasibility of using recycled coarse and fine aggregates in the production of FRHPC. Accordingly three types of fiber reinforced high performance concretes and one plain high performance concrete (PHPC) have been tried in this investigation. For comparison purposes, a Plain Cement Concrete (PCC) mix of M20 grade with a mix proportion of 1:1.5:3.3 with W/C ratio of 0.5 designed as per I.S. code method was also tried. The mix proportion for production of PHPC mixes was 576.8 Kg/m^3 of cement, 144.2 Kg/m^3 of Metakaolin, 571.0 Kg/m^3 of fine aggregate, 857.0 Kg/m^3 of coarse aggregate with a water of 234.3 liters and super plasticizer of 10.8 liters.

Steel Fiber Reinforced High Performance Concrete (SFRHPC) was produced by adding steel fibers in different volume fractions ranging from 0.50 to 1.25% to PHPC. Glass Fiber Reinforced High Performance Concrete (GFRHPC) was prepared by adding glass fibers to the PHPC in volume fractions of 0.5, 0.75, 1.0 and 1.25%. Similarly, Polypropylene Fiber Reinforced High Performance Concrete (PFRHPC) was produced by adding polypropylene fibers to PHPC in volume fractions ranging from 0.5 to 1.25%. For each type of FRHPC, three types of mixes were prepared.

- Type1: FRHPC with 100% natural coarse and fine aggregates
- Type2: FRHPC with 100% RCA + 100% natural fine aggregate
- Type3: FRHPC with 100%RCA + 100% RFA

3.2 Preparation of test specimens

Cubes of size 150 x 150 x 150mm, cylinders of 150mm diameter and 300mm height and flexure beams of size 600 x 150 x 150mm were cast and tested for determining compressive, split tensile and flexure strengths respectively. Double–L (push-off) specimens with inner dimension of 279.4mm X 203.2mm as suggested by Balaguru and Shah [27] were cast and tested for determining the shear strength (See Figure1). Disc shaped specimens of size 100mm diameter and 50mm depth were cast for conducting the Rapid Chloride Permeability Test (RCPT) for determining the chloride ion permeability. All the specimens were cured by immersion in water for a normal curing period of 28 days before testing.

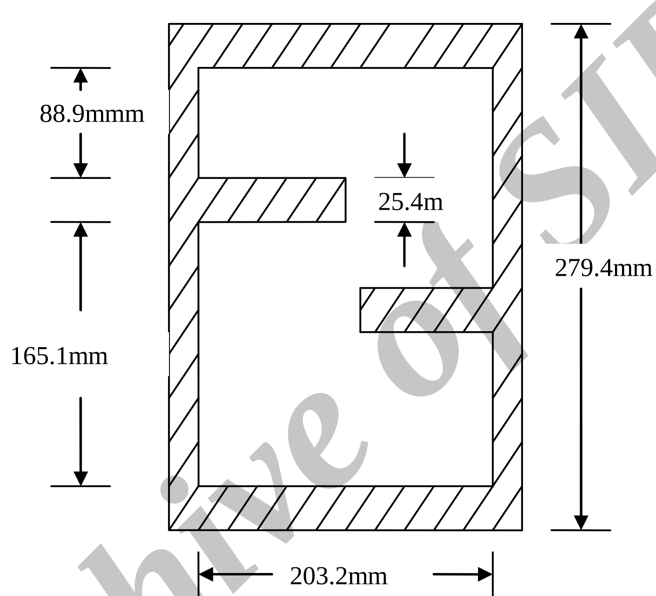

Figure 1. Plan of shear mould

3.3 Tests conducted

3.3.1 Compressive strength test

Compression test on the cubes was conducted on the 2000 kN. AIMIL – make digital compression testing machine. The pressure gauge of the machine indicating the load has a least count of 1 kN. The cube was placed in the compression-testing machine and the load on the cube is applied at a constant rate up to the failure of the specimen and the ultimate load is noted. The cube compressive strength is calculated as load per unit area and is presented in Table 2. For each mix three specimens were tested and average values are reported.

3.3.2 Split tensile strength test

Split tensile strength test is conducted on the cylindrical specimen in the 2000 kN capacity AIMIL make digital compression testing machine. The cylinders prepared for testing are 150mm in diameter and 300mm long. After noting the weight of the cylinder, diametrical lines are drawn on the two ends, such that they are in the same axial plane. Then the cylinder is placed on the bottom compression plate of the testing machine and is aligned such that the lines marked on the ends of the specimen are vertical. Then the top compression plate is brought into contact at the top of the cylinder. The load is applied at uniform rate, until the cylinder fails and corresponding load is recorded (P). From this load, the splitting tensile strength is calculated for each specimen from Equation 1 and the results are presented in Table 2. For each mix, three specimens were tested and average values are reported.

$$\text{Split tensile strength (MPa)} = \frac{2P}{\pi DL} \tag{1}$$

Where, D and L are diameter and length of cylinder specimen.

3.3.3 Flexure strength test

The Two-Point bending test is conducted on a loading frame to determine the flexural strength on beam specimens of size 600 x 150 x 150mm. The beam element is simply supported on two rollers of 4.5 cm diameter over a span of 450 mm. The loading was applied on the specimen through hydraulic jacks and was measured using a 500 kN pre-calibrated proving ring. The bending moment (M) on the beam specimen has been calculated from the recorded flexural load and the flexural strength is calculated as the ratio of the bending moment and section modulus of the beam specimen and is presented in Table 2. For each mix three specimens were tested and average values are reported.

Table 2: Results of experimentation

Type of Fibre	**Mix Design-ation**	**Fibre volume fraction(%)**	**Compressive strength (MPa)**			**Split tensile strength (MPa)**			**Flexure strength (MPa)**			**Shear strength (MPa)**		
			NA	RCA	RCA+ RFA	NA	RCA	RCA+ RFA	NA	RCA	RCA+ RFA	NA	RCA	RCA+ RFA
---	PCC	0.00	27.9	23.8	22.7	2.92	2.51	2.42	3.95	3.51	3.28	7.43	6.68	6.51
---	PHPC	0.00	80.2	67.1	64.9	5.68	4.98	4.69	6.79	5.93	5.81	21.63	19.77	19.18
Steel fibre	SFRHPC	0.50	85.1	72.6	69.6	6.67	5.94	5.68	8.06	7.21	7.14	25.91	23.89	22.91
		0.75	87.3	76.2	74.8	6.92	6.36	6.13	8.59	7.84	7.86	26.79	25.09	24.39
		1.00	92.8	84.8	79.7	7.21	7.11	6.64	9.48	8.92	7.58	31.28	31.18	29.45
		1.25	91.2	83.1	78.4	6.83	6.91	6.36	8.93	8.66	7.32	30.76	30.93	28.72
Glass fidbre	GFRHPC	0.50	82.3	71.3	68.9	6.36	5.62	5.23	7.82	6.95	6.88	22.86	21.26	20.59
		0.75	83.5	72.7	72.1	6.48	6.03	5.72	8.16	7.34	7.41	23.98	22.44	22.03
		1.00	88.4	83.4	78.3	6.59	6.76	6.16	8.97	8.41	8.07	25.59	23.91	23.11
		1.25	87.2	81.7	77.4	6.96	6.33	5.97	8.64	8.28	7.81	24.82	22.18	22.83
Poly Propylene fibre	PFRHPC	0.50	83.9	71.8	71.2	6.41	5.93	5.51	7.81	7.17	6.94	25.16	22.86	22.51
		0.75	86.2	74.7	73.4	6.83	6.27	5.86	8.41	7.52	7.62	27.69	26.19	23.09
		1.00	91.1	84.5	78.6	7.29	6.91	6.51	9.28	8.81	8.57	29.71	28.88	27.67
		1.25	89.6	82.9	76.7	6.96	6.62	6.26	8.91	8.53	8.22	28.24	27.69	26.96

3.3.4 Shear strength test

Double –L (push-off) specimens with inner dimension of 279.4mm×203.2mm with a wall thickness of 12.7mm as shown in Figure 1 have been used to determine the shear strength. After curing, grooves are cut along the shear plane to induce shear failure.

Shear tests were conducted on shear specimens in a standard compression testing machine. The movement along the shear plane was measured using a dial gauge. The dial gauge was mounted on steel angles attached to the specimen using epoxy. The failure load has been recorded for each specimen. The shear strength is calculated as load per unit shear area and is presented in Table 2. For each mix three specimens were tested and average values are reported.

3.3.5 Rapid chloride permeability test (RCPT)

In the present work, the Rapid Chloride Permeability Test (RCPT) apparatus has been used to determine the chloride permeability (See Figure 2). The test set-up consists of two acrylic chambers having grooved recesses on one face and closed at the other end. The specimen can snug-fit into the open faces of the chambers. One of the cells is filled with NaCl solution (concentration 2.4 M), while the other is filled with 0.3 M NaOH solution. Copper mesh electrodes are mounted in the cells such that they are in contact with the end faces of the specimen. Long threaded rods hold the whole assembly together with wing nuts at both ends. The chamber containing NaCl solution is connected to the positive terminal and the chamber containing NaOH solution is connected to the negative terminal of the external DC voltage cell. An external voltage cell is used to apply a voltage difference of 60V between the electrodes. The electrochemical cell, constituted by this assembly, results in the rapid migration of chloride ions from the sodium chloride solution to the sodium hydroxide solution, via the pore network offered by the concrete disc shaped specimen. The movement of chloride ions is proportional to the intensity of electric current as measured by an ammeter in the power source. The test is carried out for duration of 6 hours and the current is measured at 15 minute intervals. The chloride ion permeability is computed as the total charge passed through by using the Equation 2.

$$\text{Chloride ion permeability in Coulombs} = (I_0 + I_1 + I_2 + I_4 + I_5)mA \times 0.001 \times 60 \times 60 \qquad (2)$$

Where, I_0, I_5 are the initial and final currents

I_1, I_2, I_3 and I_4 are the intermediate currents

For each mix three specimens were tested and average values are reported in Table 2.

Figure 2. Chloride ion permeability test setup

4. DISCUSSION OF TEST RESULTS

The results of various strength tests conducted on different concrete mixes are presented in Table 2 and a discussion is presented in the following sections to examine the feasibility of using recycled coarse and fine aggregates in the production of FRHPC.

4.1 Effect of percentage of fibers

4.1.1 Compressive strength

For all the FRHPC mixes tried in this investigation, the compressive strengths were found to increase with the increase in fiber volume fraction up to 1.00% but there was decrease in compressive strengths at fiber volume of 1.25%. This is true even for FRHPC mixes prepared with recycled coarse and fine aggregates. As an example, the variation of compressive strength of SFRHPC is plotted in Figure 3. It can be seen from this figure that the compressive strength of all SFRHPC mixes prepared using RCA as well as RCA+RFA increased with increase in fiber content up to 1%. Similar trends can be noticed from Table 2 even for GFRHPC and PFRHPC also. This trend is expected because the fibers add to the strength and stiffness of concrete. Maximum compressive strengths are achieved at fiber volume fraction of 1.00% in the ranges tested. But a decrease in compressive strengths was observed at a fiber volume of 1.25% for all FRHPC mixes. At 1.25%, balling of fibers was observed. The trend was the same for the GFRHPC and PFRHPC mixes prepared with RCA and RCA+RFA mixes also. This reduction is mainly because of the balling effect, arising due to the increase in the fiber content.

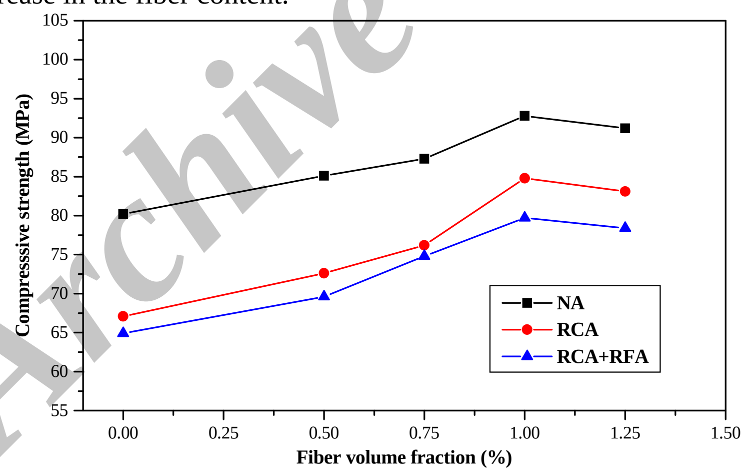

Figure 3. Variation of compressive strength of SFRHPC

When compared to reference concrete PHPC, the increase in compressive strength is in the range of 6.11 to 15.71%, 2.62 to 10.22%, and 4.61 to 13.59% respectively for SFRHPC, GFRHPC and PFRHPC mixes prepared using natural aggregates (NA). Similarly for SFRHPC, GFRHPC and PFRHPC mixes prepared using RCA, the increase in compressive strengths are in the ranges of 8.19 to 26.38%, 6.26 to 24.29%, and 7.00 to 25.93% respectively. For SFRHPC, GFRHPC and PFRHPC mixes prepared using RCA+RFA, the increase in compressive strengths are in the ranges of 7.24 to 22.8%, 6.16 to 20.65%, and 9.71 to 21.11% respectively. Additions of fibers are contributing for higher percentage increase in compressive strength for RCA as compared to NA.

The compressive strengths of all FRHPC mixes are considerably higher than the reference M20 grade concrete (PCC). When compared to reference concrete PCC, the increase in compressive strength is in the range of 205.0 to 232.6%, 205.0 to 256.3%, 206.6 to 251.1% respectively for SFRHPC mixes prepared with NA, RCA and RCA+RFA. Similarly for GFRHPC and PFRHPC mixes prepared using NA, RCA and RCA+RFA, the increase in compressive strengths are in the ranges of 194.9 to 216.9%, 199.6% to 250.4%, 203.5 to 244.9% and 207.7 to 226.5%, 201.7 to 255.0% and 213.7 to 246.3% respectively. Thus, it can be noticed that addition of fibers have considerably improved the compressive strengths of HPC mixes prepared using recycled coarse and fine aggregates.. At the initial stages of loading, micro cracks develop inside the concrete. These cracks are intercepted by fibers which are oriented at random. The fibers which cross the cracks generally will delay the propagation of cracks and hence the cracks have to take a meandering path. During this course the material demand higher energy for the further propagation of cracks which results in higher load carrying capacity and ductility for FRHPC mixes. Also, it can be concluded that recycled coarse and fine aggregates can be successfully used in the production of fiber reinforced high-performance-concrete.

4.1.2 Split tensile strength

The split tensile strengths of all FRHPC mixes were considerably higher than that of plain concrete at all volume fractions up to 1.00%. The trend was the same even for the FRHPC mixes prepared with RCA and RCA+RFA. The percentage increase in tensile strength of FRHPC mixes when compared to that of reference mix M20 ranged from 117.8 to 149.7%, 123.9 to 183.3% and 116.1 to 174.4% prepared using NA, RCA and RCA+RFA respectively. The increase in tensile strength due to the addition of fibers is expected because of the crack arresting and crack deflection mechanisms of fibers.

As an illustration, the variation of split tensile strength of PFRHPC mixes with the fiber volume fraction is presented in Figure 4.

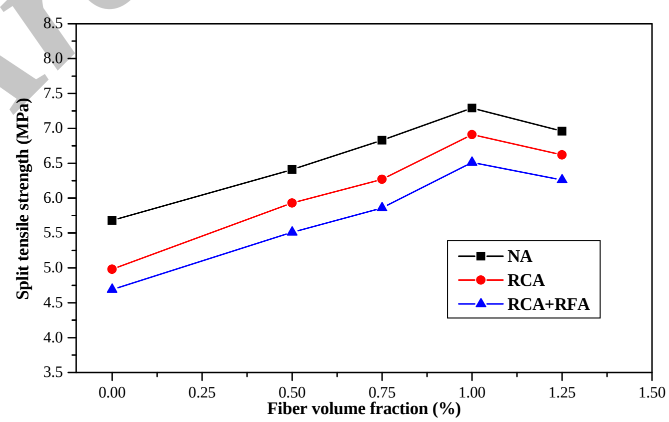

Figure 4. Variation of split tensile strength of PFRHPC

From this Figure, it can be observed that with the increase in the fiber volume the split tensile strength increased up to 1.00% due to increase in tensile load carrying capacity because of presence of fibers. But, later on at 1.25% of fiber volume there is decrease in the tensile strength due to balling effect. The same trend is observed even for the GFRHPC and SFRHPC mixes prepared using NA, RCA and RCA+RFA (see Table.2).

When compared to reference concrete PHPC, the increase in tensile strength is in the range of 17.43 to 26.94%, 11.97 to 16.02%, and 12.85 to 28.35% respectively for SFRHPC, GFRHPC and PFRHPC prepared using natural aggregates (NA). Similarly for SFRHPC, GFRHPC and PFRHPC prepared using RCA, the increase in tensile strengths are in the ranges of 19.28 to 42.77%, 12.85 to 35.74% and 19.08 to 38.76% respectively. For SFRHPC, GFRHPC and PFRHPC prepared using RCA+RFA, the increase in tensile strengths are in the ranges of 21.11 to 41.58%, 11.51 to 31.34% and 17.48 to 38.81% respectively. Interestingly it can be observed that the percentage increase in tensile strength due to addition of fibers is more in recycled aggregate concrete.

4.1.3 Flexural strength

The flexural strengths of all FRHPC mixes were found to increase with the increase in fiber volume fraction up to 1.00% but there was decrease in flexural strengths at fiber volume of 1.25%. This is true even for FRHPC mixes prepared with recycled coarse and fine aggregates. As an example, the variation of flexural strength of GFRHPC with fiber volume is illustrated in Figure5. It can be observed that with the increase in fiber volume the flexural strength also increases up to 1.00% but later on there is decrease in the flexural strength. The same trend is observed even for the SFRHPC and PFRHPC mixes prepared with NA, RCA and RCA+RFA.

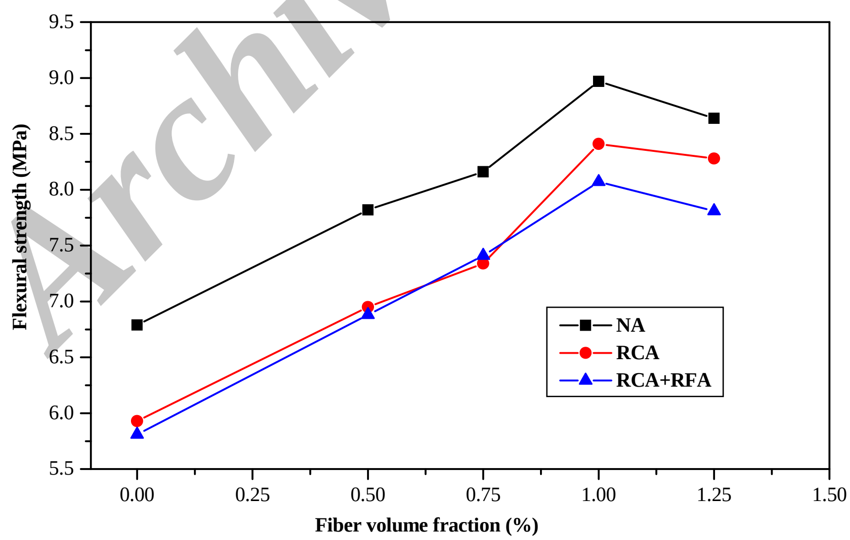

Figure 5. Variation of flexural strength of GFRHPC

When compared to that of PHPC, the percentage increase in flexural strength of SFRHPC mixes ranged from 18.7 to 39.62%, 21.59 to 50.42% and 22.89 to 35.28% respectively for the mixes prepared using NA, RCA and RCA+RFA. Similarly for GFRHPC and PFRHPC mixes prepared using NA, RCA and RCA+RFA, the percentage increase ranged from 15.17 to 32.11%, 17.2 to 41.82%, 18.42 to 38.89% and 15.02 to 36.67%, 20.91 to 48.57% and 19.45 to 47.50% respectively. Interestingly it can be observed that the percentage increase in flexural strength due to addition of fibers is more in recycled aggregate concrete.

When compared to PCC mixes prepared using NA, RCA and RCA+RFA the percentage increase in flexural strength are in the ranges of 97.7 to 140.0%, 98.0 to 154.1% and 109.8 to 161.3% respectively for SFRHPC, GFRHPC and PFRHPC. As the flexural strengths of all FRHPC mixes prepared with RCA and RCA+RFA are comparatively higher (see Table 2) than that of corresponding PCC mixes, it can be concluded that recycled aggregates can safely be used in production of FRHPC.

4.1.4 Shear strength

From Table 2, it can be observed that the shear strength of all FRHPC mixes increased with the increase in the fiber volume fraction up to 1.00%. But a decreasing trend is observed at fiber volume of 1.25% due to the balling effect. Also it is observed that there is considerably increase in shear strength of FRHPC mixes when compared to that of PCC. The increase in shear strength is in the range of 237.8% to 320.9%, 207.7% to 244.4% and 238.6% to 299.9% for SFRHPC, GFRHPC and PFRHPC mixes prepared with NA compared to corresponding PCC mixes. Similarly for SFRHPC, GFRHPC and PFRHPC prepared using RCA, the increase in shear strengths are in the ranges of 257.6% to 366.8%, 218.3% to 257.9%, and 242.2% to 332.3% respectively. For SFRHPC, GFRHPC and PFRHPC prepared using RCA+RFA, the increase in shear strengths are in the ranges of 251.9% to 352.4%, 216.3% to 254.9%, and 245.8% to 325.0% respectively.

When compared to that of PHPC prepared using NA, the percentage increase in shear strength is in the range of 19.79 to 44.61%, 5.69 to 18.31% and 16.32 to 37.36% for SFRHPC, GFRHPC and PFRHPC respectively. Similarly for SFRHPC, GFRHPC and PFRHPC prepared using RCA, the increase in shear strengths are in the ranges of 20.84% to 57.71%, 7.54% to 20.94%, and 15.63% to 46.08% respectively. The increase in shear strengths are in the range of 19.45 to 53.55%, 7.35 to 20.49% and 17.36 to 44.26% respectively for SFRHPC, GFRHPC and PFRHPC mixes prepared with RCA+RFA.

4.1.5 Chloride ion permeability

The results of chloride ion permeability tests conducted on various FRHPC mixes have been presented in Table 3. It can be observed that with the increase in the fiber volume the chloride ion permeability decreases. This is true for all the three types of FRHPC mixes tried in this investigation. As an example, the variation of chloride ion permeability of SFRHPC with fiber volume is illustrated in Figure 6. It can be observed from this Figure that the chloride ion permeability of SFRHPC decreases with increase in fiber content in the ranges tested. Similar trend has been noticed for other two types of FRHPC mixes.

Table 3: Chloride ion permeability values

Type of fibre	Mix designation	Fibre volume fraction (%)	Chloride permeability (Coulombs)		
			NA	RCA	RCA+RFA
---	PCC	0.0	3906	6372	6869
---	PHPC	0.0	542	893	942
Steel fibre	SFRHPC	0.5	463	786	817
		0.75	456	713	739
		1.00	395	562	568
		1.25	312	531	514
Glass fibre	GFRHPC	0.5	495	816	838
		0.75	487	753	776
		1.00	424	596	581
		1.25	349	557	546
Poly Propylene fibre	PFRHPC	0.5	484	802	827
		0.75	471	731	754
		1.00	412	584	577
		1.25	327	546	525

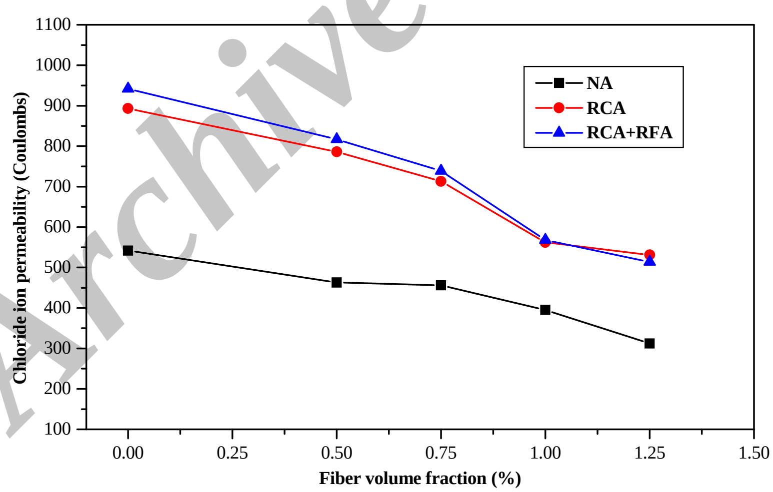

Figure 6. Variation of chloride ion permeability of SFRHPC

The percentage decrease in chloride ion permeability of FRHPC mixes prepared using NA, RCA and RCA+RFA over corresponding PCC mixes are in the ranges of 87.33% to 92.01%, 87.19% to 91.67% and 87.8% to 92.52% respectively. When compared to that of PHPC, the percentage decrease in chloride ion permeability of SFRHPC mixes prepared using NA, RCA and RCA+RFA ranged from 14.57 to 42.44%, 11.99 to 40.54% and 13.27

to 45.44% respectively. Similarly for GFRHPC and PFRHPC mixes prepared using NA, RCA and RCA+RFA, the percentage decrease ranged from 8.67 to 35.61%, 8.62 to 37.63%, 11.04 to 42.04% and 10.7 to 39.67%, 10.19 to 38.86% and 12.21 to 44.27% respectively. Also it is observed that with the addition of fibers the chloride ion permeability of all FRHPC mixes is falling below 1000 Couloumbs, which is classified as very low permeability as per ASTM C-1202 classification as shown in Table 4.

Table 4: Classification of permeability as per ASTM C-1202

Charge (coulombs)	Permeability
>4000	High
2000-4000	Moderate
1000-2000	Low
1000-100	Very Low
<100	Negligible

4.2 Effect of type of fibers

4.2.1 Compressive strength

It can be noticed from Table 2**,** that among the three types of fibers used, steel fibers contributed maximum compressive strengths and minimum contributions were recorded with glass fibers. The increase in compressive strengths of SFRHPC mixes prepared using NA, RCA and RCA+RFA over corresponding GFRHPC mixes are in the ranges of 3.3 to 4.7%, 1.7 to 4.6% and 1.01 to 3.6% respectively. Similarly, the increase in strengths over corresponding PFRHPC mixes are in the ranges of 1.3 to 1.8%, 0.24 to 1.96% and 1.4 to 2.2% respectively. Similarly, the increase in compressive strengths of PFRHPC with NA, RCA and RCA+RFA over corresponding GFRHPC mixes ranged from 1.97 to 3.13%, 0.7 to 2.7% and 0.38 to 3.2% respectively. Hence it can be concluded that polypropylene fibers are performing better as they are stiffer than that of glass fibers. Steel fibers are performing better than that of polypropylene and glass fibers as main function of the steel fibres is to resist the opening of cracks due to micro-cracking and increase the ability of the composite to withstand loads.

4.2.2 Split tensile strength

It can be observed from Table 2, that steel fibrous HPC mixes have attained higher tensile strengths as compared to glass fibers and polypropylene fibrous HPC mixes. The tensile strengths of GFRHPC and PFRHPC mixes prepared using NA over corresponding SFRHPC mixes decreased in the range of 4.9 to 9.4% and 1.3 to 4.1% respectively. Similarly with RCA and RCA+RFA the decrease in the tensile strengths is in the range of 5.2 to 9.2%, 0.2 to 4.4% and 6.5 to 8.6%, 1.6 to 4.6% respectively. PFRHPC mixes performed better when compared to that of GFRHPC mixes. The decrease in tensile strengths of GFRHPC prepared using NA, RCA and RCA+RFA over corresponding PFRHPC mixes are in the ranges of 0.8 to 10.6%, 2.2 to 5.5% and 2.4 to 5.7% respectively. Uniform, cohesive mix was possible by the use of polypropylene fibers when compared to that of glass fibers hence they achieved higher strengths

4.2.3 Flexural strength

The flexural strength results of the present investigation are presented in Table 2. Maximum flexural strengths were contributed by the use of steel fibers and minimum are recorded with glass fibers. The increase in flexural strengths of SFRHPC mixes prepared using NA, RCA and RCA+RFA over corresponding GFRHPC mixes are in the ranges of 2.9 to 5.4%, 0.4 to 6.4% and 3.6 to 5.7% respectively. Similarly in increase in strengths over PFRHPC mixes are in the ranges of 0.2 to 3.1%, 0.6 to 4.1% and 2.8 to 3.1% respectively. Polypropylene based HPC mixes with NA, RCA and RCA+RFA recorded higher flexural strengths than that of corresponding glass fibrous HPC mixes and the increase in flexural strengths are in the ranges of 2.4 to 3.3%, 2.4 to 4.5% and 1.3 to 5.8% respectively.

4.2.4 Shear strength

From Table 2, it can be observed that the shear strength of all SFRHPC mixes is higher when compared to corresponding GFRHPC and PFRHPC mixes. As an illustration, the variation of increase in shear strengths of FRHPC mixes at 1.00% of fiber volume as compared to PHPC is presented in Figure 7.

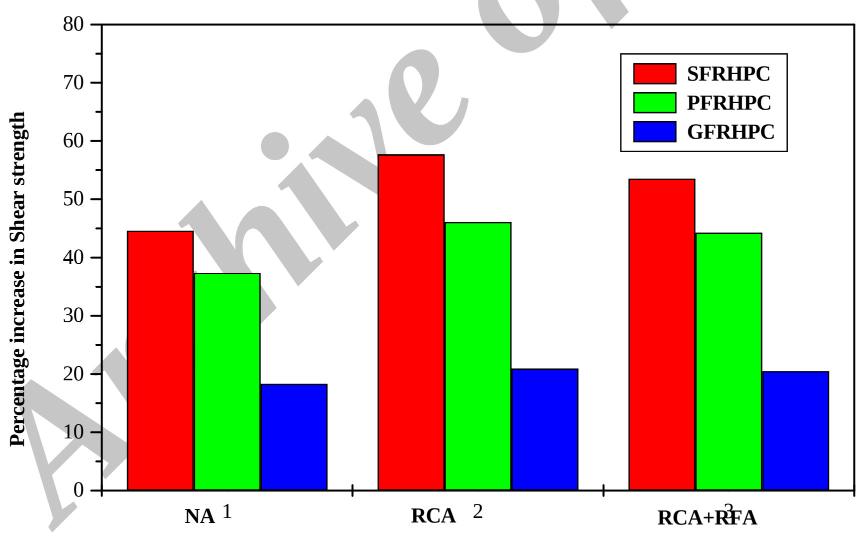

Figure 7. Increase in shear strength for FRHPC at 1.00% as compared to PHPC

From the figure, it can be observed that SFRHPC mixes recorded maximum shear strengths and minimum were recorded by GFRHPC mixes. The increase in shear strengths of SFRHPC prepared using NA over corresponding GFRHPC and PFRHPC mixes are in the ranges of 10.5 to 19.3% and 2.9 to 8.2%, those prepared with RCA are in the ranges of 10.6 to 28.3% and 4.3 to 10.5% and those with RCA+RFA are in the ranges of 9.7 to 21.5% and 1.7 to 6.1% respectively. Similarly polypropylene HPC mixes recorded higher strengths than that of glass fibrous HPC mixes and the increase in shear strengths prepared using NA, RCA and RCA+RFA are in the ranges of 9.1 to 13.9%, 6.9 to 19.9% and 4.6 to 16.5% respectively.

4.2.5 Chloride ion permeability

The results of chloride ion permeability tests conducted on various fibrous concrete mixes have been presented in Table 3. It can be observed from this Table 3 that the chloride ion permeability of SFRHPC mixes is less when compared to that of HPC mixes prepared with polypropylene and glass fibers. The decrease in chloride ion permeability of SFRHPC mixes prepared with NA, RCA and RCA+RFA over corresponding GFRHPC mixes ranged from 6.9 to 11.9%, 3.8 to 6.0%, 2.3 to 6.2% respectively and that for PFRHPC mixes ranged from 3.3 to 4.8%, 2.0 to 3.9% and 1.2 to 2.1% respectively. The reduction achieved in chloride ion permeability with the introduction of steel fibers in concrete may be due to reduction in plastic and drying shrinkage cracks. Also it is observed that HPC mixes prepared with polypropylene fibers are less permeable when compared to that of mixes with glass fibers. The decrease in the chloride ion permeability of PFRHPC mixes prepared with NA, RCA and RCA+RFA are in the ranges of 2.3 to 6.7%, 1.7 to 3.0% and 0.7 to 4.0% respectively.

4.3 Effect of recycled aggregates

4.3.1 Compressive strength

It can be noticed from Table 2 that the compressive strengths of SFRHPC mixes prepared with RCA are less compared to those prepared using NA. Further reduction in compressive strength is noticed for mixes prepared using RCA+RFA. This trend is similar even for GFRHPC and PFRHPC mixes also. The reason may be attributed due to the fact that presence of high water content inside the recycled aggregates may result in bleeding during casting; consequently the compressive strength of concrete is reduced. The maximum reduction in compressive strength due to RCA is 17.2%, 15.4% and 16.9% for SFRHPC, GFRHPC and PFRHPC respectively. From Table 2 it can also be observed that maximum loss of compressive strength due to the use of RCA+RFA is about 22.3% for SFRHPC, GFRHPC and PFRHPC. As an illustration, the decrease in compressive strength of FRHPC at 1.00% as compared to NA is presented in Figure 8.It can be observed from the figure that the percentage decrease in compressive strength is more pronounced in FRHPC mixes with RCA+RFA than those mixes with RCA alone. The same trend is observed at all fiber volumes. The reduction in compressive strength due to RCA+RFA when compared to that of mixes with RCA are in the ranges of 1.9 to 6.4%, 0.8 to 6.5% and 0.8 to 8.1% respectively for HPC mixes with steel fibers, glass fibers and polypropylene fibers. Thus the reduction in strengths due to the use of recycled fines is marginal. Hence, it can be concluded that recycled fines can also be safely be used in the production of FRHPC works thus saving the natural sand.

4.3.2 Split tensile strength

It can be observed from Table 2 that the maximum split tensile strengths were recorded for mixes prepared with NA followed by mixes prepared with RCA and RCA + RFA. As an example, the variation of percentage decrease in tensile strength of FRHPC at 0.75% fiber volume as compared to that of mixes with NA is plotted in Figure 9.

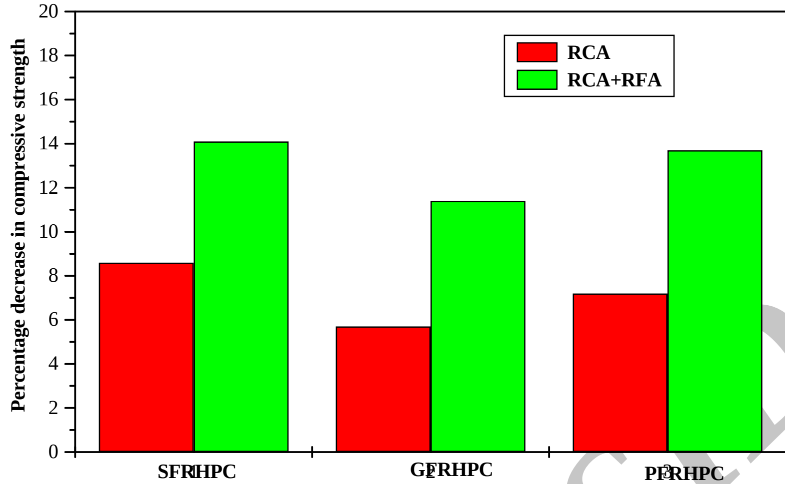

Figure 8. Decrease in compressive strength of FRHPC at 1.00% as compared to NA

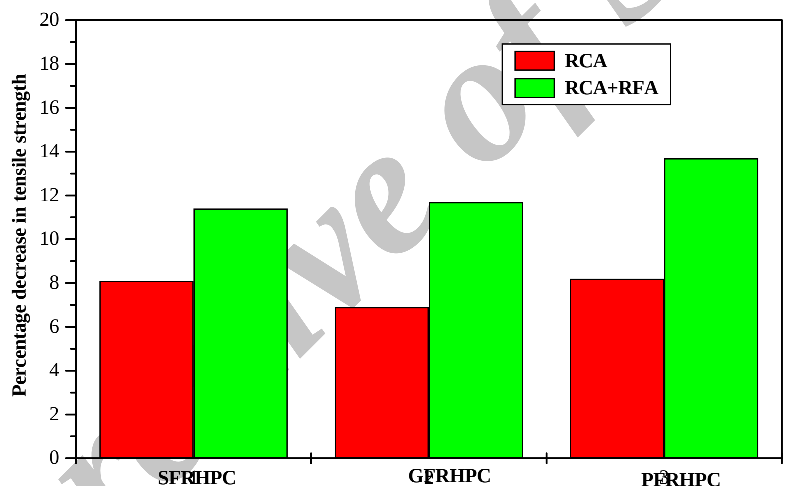

Figure 9. Decrease in tensile strength of FRHPC at 0.75% as compared to NA

It can be observed that for all the three types of fibers tried in the work, the FRHPC mixes with RCA+RFA are suffering marginal loss of tensile strength than that of mixes with RCA alone. The trend is observed to be the same at all fiber volumes. Usage of recycled aggregates contributed lower tensile strengths due to the residual impurities on the surface of recycled aggregates which blocked the strong bond between the cement paste and aggregates.

The percentage decrease in tensile strength due to RCA in the FRHPC mixes is in the range of 1.4 to 12.3%, 9.9 to 13.2% and 5.5 to 8.9 % respectively for SFRHPC, GFRHPC and PFRHPC. Similarly the percentage decrease in tensile strength due to RCA+RFA is in the range of 7.4 to 17.4%, 6.9 to 21.6% and 11.2 to 16.6% respectively for SFRHPC, GFRHPC and PFRHPC mixes. The maximum reduction in tensile strength due to RCA+RFA when compared to that with RCA alone is 8.6%, 9.7% and 7.6% respectively for

SFRHPC, GFRHPC and PFRHPC. It can also be observed that the split tensile strengths of fibrous HPC mixes prepared using RCA + RFA are marginally less than those prepared with RCA alone. Hence, RCA + RFA can safely be used in preparing FRHPC mixes also.

4.3.3 Flexural strength

The flexural strength results of the present investigation are presented in Table 2. From this Table 2, it can be noticed that the reduction in flexural strengths of SFRHPC, GFRHPC and PFRHPC mixes with RCA when compared to those corresponding mixes with NA are in the ranges of 3.1 to 11.8%, 4.3 to 12.5% and 4.5 to 11.8% respectively. Similarly for the SFRHPC, GFRHPC and PFRHPC mixes with RCA+RFA the decrease in flexural strengths are in the ranges of 9.3 to 25.1%, 10.1 to 13.7% and 8.3 to 12.5% respectively. The reduction in flexural strengths due to use of recycled aggregates may be attributed due to higher water absorption capacity when compared to that of natural aggregates. As an illustration, the decrease in flexural strength of FRHPC with RCA and RCA+RFA at 0.5% fiber volume as compared to mixes with NA is presented in Figure 10. It can be observed from the figure that for all FRHPC mixes with RCA the percentage decrease in flexural strengths is marginally less when compared to those with RCA+RFA. The trend is the same at all fiber volumes. Also it can be observed from Table 2 that the flexural strengths of all FRHPC mixes with RCA+RFA are marginally less than those with RCA alone. The maximum reduction in flexural strengths is 18.3%, 6.0% and 3.8% respectively for SFRHPC, GFRHPC and PFRHPC. Thus the reduction in flexural strength due to RCA + RFA is observed to be marginal. Accordingly, the use of recycled fine aggregates in fiber reinforced HPC can be viewed as viable solution in saving the natural river sand.

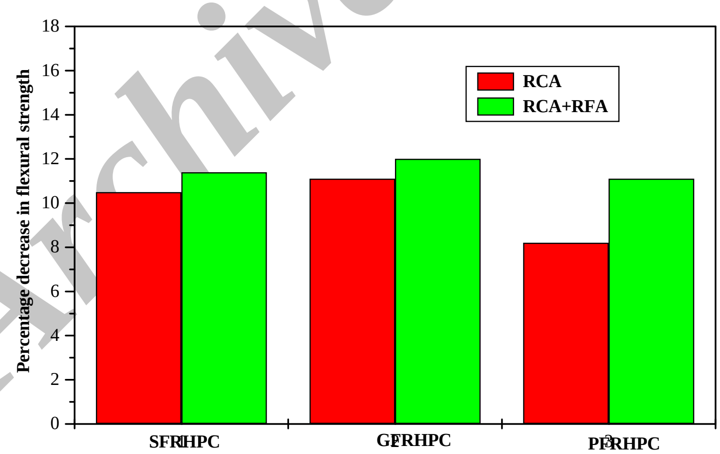

Figure 10. Decrease in flexural strength of FRHPC at 0.5% as compared to NA

4.3.4 Shear strength

It can be noticed from Table 2 that the shear strengths of SFRHPC mixes prepared with RCA are less compared to those prepared using NA. Further reduction in shear strength is noticed for mixes prepared using RCA+RFA. The reason for the decrease in strength is the recycled aggregates being more porous than that of natural aggregate. This increased porosity may lower the bond strength between the cement paste and the aggregate thus, leading to the loss of strength and increase in permeability. This trend is similar even for GFRHPC and PFRHPC mixes also. The reduction in shear strength due to RCA is in the range of 0.3 to 8.5%, 7.0 to 11.9% and 2.9 to 10.1% respectively for SFRHPC, GFRHPC and PFRHPC. Similarly the decrease in shear strength for mixes with RCA+RFA are in the ranges of 7.1 to 13.1%, 8.7 to 11.0% and 4.7 to 11.8% respectively for SFRHPC, GFRHPC and PFRHPC mixes. As an illustration, the decrease in shear strength of FRHPC at 0.5% as compared to NA is presented in Figure 11. From this figure it can be observed that the percentage decrease in shear strengths of all the FRHPC mixes with steel fibers, glass fibers and polypropylene fibers prepared with RCA+RFA is higher than those with RCA. The trend is the same at all fiber volumes. The maximum reduction in shear strengths for FRHPC mixes with RCA+RFA is 7.7%, 3.4% and 13.4% respectively for SFRHPC, GFRHPC and PFRHPC. It can also be observed from Table 2 that the shear strengths of fibrous concrete mixes prepared using RCA + RFA are marginally less than those prepared with RCA alone. Hence, RCA + RFA can safely be used in preparing fiber reinforced HPC mixes.

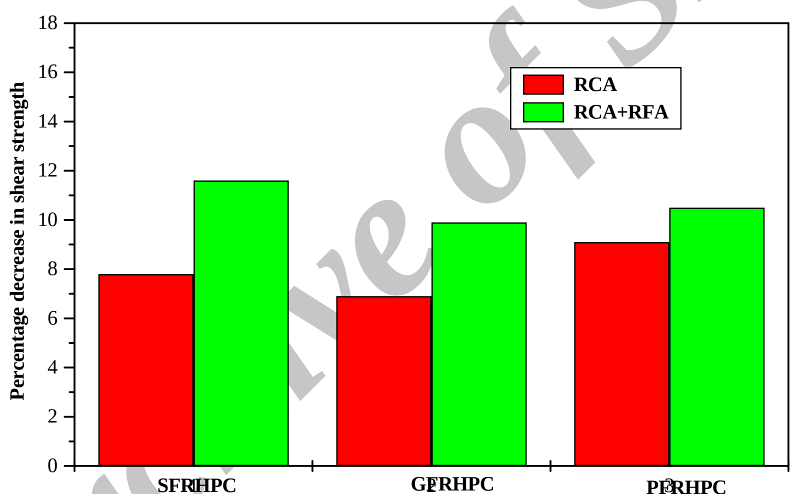

Figure 11. Decrease in shear strength of FRHPC at 0.5% as compared to NA

4.3.5 Chloride ion permeability

The results of chloride ion permeability tests conducted on various FRHPC mixes have been presented in Table 3. It can be noticed from Table 3 that the chloride ion permeability of SFRHPC mixes prepared with RCA are more compared to those prepared using NA. Further increase in chloride ion permeability is noticed for mixes prepared using RCA+RFA. The reason for this phenomenon to happen is recycled aggregates having higher water absorption than that of natural aggregates. The porosity of the adhered mortar causes the water to penetrate into the excessive pores and leads to an increase in water absorption capacity thus increasing the chloride ion permeability. This trend is similar even for GFRHPC and PFRHPC mixes also. As an example the variation of chloride ion permeability of SFRHPC mixes with fiber volume is presented in Figure 12. From this figure, it can be observed that the chloride ion permeability of mixes prepared with RCA or RCA + RFA are considerably higher than those prepared with NA, as the recycled aggregates is more porous when compared to that of natural aggregate, which is considered as impervious inert filler. The trend is the same for GFRHPC and PFRHPC mixes also. The maximum increase in chloride ion permeability of FRHPC mixes with RCA is in the range of 41.2%, 39.3% and 40.1% for SFRHPC, GFRHPC and PFRHPC. Similarly percentage increase in chloride ion permeability of FRHPC mixes with RCA+RFA over corresponding FRHPC mixes with NA are in the ranges of 30.5 to 43.3%, 27.0 to 40.9% and 28.9 to 41.5% respectively for SFRHPC, GFRHPC and PFRHPC mixes.

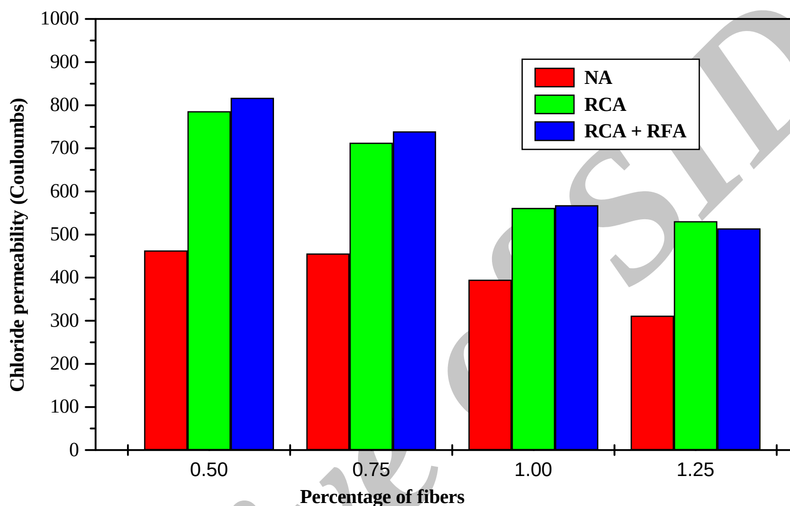

Figure 12. Chloride ion permeability of SFRHPC mixes

Though there is increase in chloride ion permeability with the usage of recycled aggregates, it can be observed from Table 3, that the chloride ion permeability values of all FRHPC mixes are less than 1000 coulombs which is classified as very low permeability as per ASTM C-1202 presented in Table 4. Hence, use of recycled aggregates is not a constraint in the production of FRHPC. It is also observed that there is marginal increase in chloride ion permeability for the mixes prepared with RCA + RFA when compared to those prepared with RCA alone. This trend is the same for all the FRHPC mixes tried in this investigation. The maximum increase in chloride ion permeability due to RCA+RFA is 3.8%, 2.9% and 3.1% respectively for SFRHPC, GFRHPC and PFRHPC. Hence it can be said that recycled fine aggregate can safely be used in the production of FRHPC thus saving the usage of natural sand.

5. CONCLUSIONS

The feasibility of using recycled coarse and fine aggregates in the production of fiber reinforced high performance concrete has been investigated in this paper. Compressive, tensile, flexural and shear strengths of three types of fiber reinforced HPC mixes prepared with steel, polypropylene and glass fibers are evaluated from the experimental results. Rapid chloride permeability values of FRHPRAC mixes. The results indicate that compressive, tensile, flexural and shear strengths decreased marginally with the use of recycled coarse and fine aggregates and hence they can be used in the production of FRHPC.

The major conclusions are:

1. The compressive, tensile, flexural and shear strengths of fiber reinforced high performance recycled aggregate concrete mixes increased with the increase of fiber content up to 1.0% and decreased beyond 1.0% fiber volume fraction. Balling of fibers at 1.25% volume fraction is mainly responsible for reduction in strengths. Maximum compressive, tensile, flexural and shear strengths are achieved at 1.0% fiber volume for all the three types of fibers used.
2. Out of the three, steel fibers contributed for higher strengths when compared to glass and poly propylene fibers.
3. The use of recycled coarse aggregate resulted in loss of compressive, tensile, flexural and shears strengths in FRHPC mixes.
4. When compared to FRHPC mixes prepared with RCA, use of RCA+RFA resulted only in marginal loss of strengths. Hence, recycled fines can be used safely in the production of FRHPC.
5. Interestingly, the percentage increase in strengths due to addition of fibers, is observed to be more in mixes prepared with recycled aggregates than those prepared with natural aggregates.
6. Addition of fibers decreased the chloride ion permeability of all HPC mixes prepared with natural or recycled aggregates. For all FRHPC mixes, the chloride ion permeability decreases as the percentage fiber volume increases in the ranges tested.
7. The chloride ion permeability of FRHPC mixes prepared with recycled aggregates is higher when compared to corresponding mixes prepared with natural aggregates. In spite of this, it is observed that all FRHPC mixes prepared using recycled coarse and fine aggregates have the chloride ion permeability values less than 1000 classified as very low permeability as per ASTM C-1202 (Table 4).

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