Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

Vol. 9	No. 1	pp. 179-188	2010

Original Research Paper

Strength and Permeability Characteristics of Fibre Reinforced Recycled Aggregate Concrete with Different Fibres

Vaishali G. Ghorpade and H. Sudarsana Rao
Department of Civil Engineering, J. N. T. U. College of Engineering, Anantapur-515 002 A.P., India

Nat. Env. Poll. Tech.
ISSN: 0972-6268
www.neptjournal.com

Key Words:
Recycled aggregate
Fibre reinforced concrete
Chloride ion permeability
Glass fibres
Poly propylene fibres
Steel fibres

ABSTRACT

Utilization of recycled aggregates in the production of concrete is now given lot of emphasis as it is viewed as an effective waste management practice, which can substantially contribute for the reduction of environmental deterioration. At the same time this is a cost effective technology saving natural resources. Recycled Aggregate Concrete (RAC) is now being used in many sectors of the construction 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 Fibre Reinforced Concrete (FRC). This paper presents the results of experimentation conducted to evaluate the strength and permeability characteristics of FRC produced with recycled coarse and fine aggregates. Three types of fibres viz., steel, glass and polypropylene were used in the production of FRC. Compressive, tensile, flexural and shear strengths of Fibre Reinforced Recycled Aggregate Concrete (FRRAC) have been evaluated from the experimentation. Chloride ion permeability has been determined as measure of permeability of FRRAC. The results of the study show that recycled coarse and fine aggregates can be successfully used in production of fibre reinforced concrete.

INTRODUCTION

Recycled aggregates are produced from the reprocessing of waste materials, the largest source being construction and demolition (C&D) waste. According to Commonwealth Scientific and Industrial Research Organization (CSIRO), C&D waste makes 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 aggregates in concrete opens a whole new range of possibilities in the reuse of materials in the building industry. With the introduction of legislation in the form of rules and regulations in many parts of the world, more emphasis is being placed on the utilization of recycled aggregates in the production of concrete as a waste management technique for sustainable construction. The effective management of C&D waste not only saves the natural resources, which are being hugely depleted due to high quantity of concrete production, but also cost effective. The use of recycled aggregate concrete (RAC) is viewed as an effective attempt to conserve 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 (Dhir et al. 1999, Poon et al. 2002, Xiao et al. 2005, Khaldoun Rahal 2007, Ann et al. 2008). 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 (Meinhold et al. 2001, Limbachiya 2004). Studies concerning the structural behaviour of recycled aggregate concrete structural elements are also reported in literature (Konno et al. 1997, Han et al. 2001, Maruyma et al. 2004, Sogo et al. 2004, Xiao & Lan 2004). The seismic performance of RAC structural elements are also reported (Xiao & Zhu 2005, Xiao et al. 2006).

Though, the concrete is strong in compression, it is brittle under tensile loading. It is an established fact that the mechanical properties of ordinary concrete and its ductility can be enhanced significantly by the addition of randomly oriented short discrete fibres. These fibres act as crack arresters, thus, improving the performance of Fibre Reinforced Concrete (FRC). The properties of FRC depend significantly on the type, volume fraction and aspect ratio (length to diameter ratio) of fibres mixed in the concrete. Though it is established that FRC is superior to ordinary concrete in many applications, very little research has been carried out on utilizing the recycled aggregates in the production of FRC. The strength and durability properties of Fibre Reinforced Recycled Aggregate Concrete (FRRAC) are to be investigated for its better applications in construction industry. This paper presents the experimental results conducted to establish the feasibility of using recycled coarse and fine aggregates in the production of FRRAC. Three types of fibres viz., steel, glass and polypropylene fibres were used in the production of FRC. Compressive, tensile, flexural and shear strengths of Fibre Reinforced Recycled Aggregate Concrete (FRRAC) have been evaluated from the experimentation. Chloride ion permeability has been determined as measure of permeability of FRRAC.

MATERIALS AND METHODS

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.

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 was 2.61.

Natural coarse aggregate: 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 was 2.75. The maximum size of the coarse aggregate was 20mm.

Recycled aggregate: The recycled fine and coarse aggregates 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 4.75mm and 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 was 2.69 with the water absorption of 3.12% and fineness modulus of 6.42. The specific gravity of RFA was 2.71, and the water absorption of 8.2% with a fineness modulus of 2.61.

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

Fibres: Three types of fibres were used in this investigation to produce three types of FRCs. Steel fibres of 1mm diameter and 100mm length with an aspect ratio of 100 were used. Glass fibres supplied by Saint Gobain Company with a filament diameter of 14 microns and 12mm length with specific gravity of 2.68 were used. Polypropylene fibres 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.

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 FRC. Accordingly, three types of fibre reinforced concretes have been tried in this investigation. For comparison purposes, a plain cement concrete (PCC) mix of M20 grade designed as per IS code method was also tried. The mix proportion for manufacture of concrete specimens was 383.0 kg/m^3 of cement, 575.0 kg/m^3 of fine aggregate, 1265.0 kg/m^3 of coarse aggregate with a water-cement ratio of 0.6. Higher water-cement ratio of 0.6 has been adopted to satisfy the greater water demand that occurs due to the mixing of fibres and recycled aggregates.

Steel Fibre Reinforced Concrete (SFRC) was produced by adding steel fibres in different volume fractions ranging from 0.50 to 1.25% to PCC. Glass Fibre Reinforced Concrete (GFRC) was prepared by adding glass fibres to the PCC in volume fractions of 0.5, 0.75, 1.0 and 1.25%. Similarly, Polypropylene Fibre Reinforced Concrete (PFRC) was produced by adding polypropylene fibres to PCC in volume fractions ranging from 0.5 to 1.25%. For each type of FRC, three types of mixes were prepared.

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

Preparation of test specimens: Cubes of size 150 × 150 × 150mm, cylinders of 150mm diameter and 300mm length and flexure beams of size 600 × 150 × 150mm were cast and tested for determining compressive, split tensile and flexural strengths. Double-L (push-off) specimens with inner dimension of 279.4mm × 203.2mm, as suggested by Balaguru & Shah (1992), were cast and tested for determining the shear strength (Fig. 1a & 1b). 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.

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 was applied at a constant rate up to the failure of the specimen and the ultimate load was

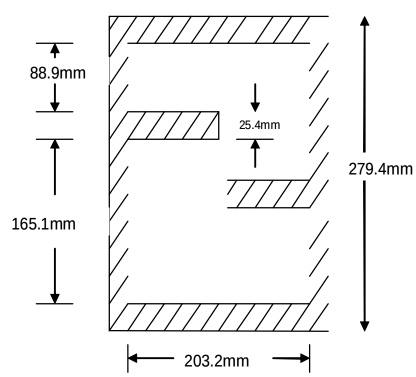

Fig.1(a): Plan of Shear mould.

Fig. 1(b): Shear moulds.

noted. The cube compressive strength was calculated as load per unit area and is presented in Table 1. For each mix three specimens were tested and average values were reported.

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

$$\text{Split tensile strength (MPa)} = \frac{2P}{pDL} \qquad ..(1)$$

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

Flexural strength test: The two-point bending test was conducted on a loading frame to determine the flexural strength on beam specimens of size 600 × 150 × 150mm. The beam element was 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 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 was calculated as the ratio of the bending moment and section modulus of the beam specimen (Table 1). For each mix three specimens were tested and average values were reported.

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 Fig. 1 (a & b) have been used to determine the shear strength. After curing, grooves were cut along the shear plane to induce shear failure.

Shear tests were conducted on shear specimens in a standard compression testing machine as shown in Fig. 2. 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 was calculated as load per unit shear area and is presented in Table 1. For each mix three specimens were tested and average values reported.

Rapid chloride permeability test (RCPT): In the present work, the Rapid Chloride Permeability Test (RCPT) apparatus has been used to determine the chloride permeability. In this test, the movement of chloride ions was proportional to the intensity of electric current as measured by an ammeter in the power source. The test was carried out for duration of 6 hours and the current was measured at 15 minute intervals. The chloride ion permeability was computed as the total charge passed through by using the equation (2).

Chloride ion permeability

$$\text{Coulombs} = (I_0 + I_1 + I_2 + I_3 + I_4 + I_5)\ \text{mA} \times 0.001 \times 60 \times 60 \qquad ...(2)$$

Where, I_0, I_5 are the initial and final currents and I_1, I_2, I_3 and I_4 are the intermediate currents.

More details about this test setup can be found in Vaishali (2006). For each mix three specimens

Table 1: Results of the experiments.

Type of Fibre	Mix design-ation	Fibre volume fraction (%)	Compressive strength (MPa)			Split tensile strength (MPa)			Flexural strength (MPa)			Shear strength (MPa)		
			NA	RCA	RCA+ RFA	NA	RCA	RCA+ RFA	NA	RCA	RCA+ RFA	NA	RCA	RCA+ RFA
-	PCC	0.00	28.1	23.3	22.6	2.98	2.59	2.48	3.90	3.48	3.31	7.46	6.72	6.48
Steel	SFRC	0.50	29.7	25.5	24.8	3.46	3.12	2.98	4.60	4.24	4.10	8.92	8.11	7.73
fibre		0.75	30.4	26.3	25.9	3.61	3.29	3.21	4.91	4.53	4.46	9.23	8.52	8.26
		1.00	32.3	29.6	28.2	3.89	3.72	3.49	5.42	5.26	4.91	10.78	10.59	9.94
		1.25	34.1	31.6	30.3	4.12	3.91	3.72	5.66	5.52	5.26	11.84	11.72	11.21
Glass	GFRC	0.50	28.6	24.6	23.8	3.31	2.96	2.80	4.46	4.10	3.98	7.87	7.21	6.94
fibre		0.75	29.1	25.4	24.9	3.42	3.16	3.05	4.66	4.28	4.24	8.26	7.62	7.46
		1.00	30.8	28.7	27.5	3.69	3.49	3.24	5.12	4.91	4.58	8.81	8.11	7.79
		1.25	32.4	30.9	29.8	3.88	3.62	3.42	5.31	5.19	4.97	9.12	8.78	8.52
Poly-	PFRC	0.50	29.2	25.2	24.6	3.37	3.06	2.94	4.53	4.18	3.98	8.67	7.79	7.62
propy		0.75	30.1	26.1	25.4	3.54	3.24	3.12	4.86	4.46	4.37	9.54	8.92	7.79
lene		1.00	31.7	29.2	27.8	3.84	3.62	3.42	5.31	5.16	4.86	10.24	9.84	9.36
fibre		1.25	33.3	31.1	30.1	3.98	3.74	3.59	5.52	5.42	5.21	11.21	10.63	10.24

were tested and average values are reported in Table 2.

RESULTS AND DISCUSSION

The results of various strength tests conducted on different concrete mixes are presented in Table 1 .

Compressive strength: The compressive strengths of all concrete mixes tried in this investigation were found to increase with the increase in fibre volume fraction. This is true even for concrete mixes prepared with recycled coarse and fine aggregates. As an example, the variation of compressive strength of SFRC is plotted in Fig. 3. It can be seen that the compressive strength of all concrete mixes prepared using RCA as well as RCA + RFA increased with increase in fibre content. Similar trends can be noticed from Table 1 even for GFRC and PFRC also. This trend is expected because the fibres add to the strength and stiffness of concrete. Maximum compressive strengths are achieved at fibre volume fraction of 1.25% in the ranges tested. When compared to reference concrete PCC, the increase in compressive strength is in the range of 5.7 to 21.4%, 1.8 to 15.3%, 3.9 to 18.5% respectively for SFRC, GFRC and PFRC prepared using natural aggregates (NA). Similarly, for SFRC, GFRC and PFRC prepared using RCA, the increase in compressive strengths are in the ranges of 9.4 to 35.6%, 5.6 to 32.6%, 8.2 to 33.5% respectively. For SFRC, GFRC and PFRC prepared using RCA + RFA, the increase in compressive strengths are in the ranges of 9.7 to 34.1%, 5.3 to 31.9%, and 8.8 to 33.2% respectively. Among the three types of fibres used, steel fibres contributed maximum compressive strengths, and minimum contributions were recorded with glass fibres. Thus, it can be noticed that addition of fibres have considerably improved the compressive strengths of concretes prepared using recycled aggregates.

It can be noticed from Fig. 3 that the compressive strengths of SFRC 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 GFRC and PFRC mixes also. The maximum reduction in compressive strength due to RCA is 14.1%, 13.1% and 13.6% respec-

Table 2: Chloride ion permeability values.

Type of Fibre	Mix Designation	Fibre volume fraction (%)	Chloride permeability (Coulombs)		
			NA	RCA	RCA+RFA
-	PCC	0.00	3906	6389	6842
Steelfibre	SFRC	0.50	3429	5572	5869
		0.75	3183	5191	5438
		1.00	2749	3896	4012
		1.25	2374	3683	3836
Glass fibre	GFRC	0.50	3573	5771	6024
		0.75	3324	5347	5581
		1.00	2912	4028	4112
		1.25	2516	3854	3921
Polypropylene fibre	PFRC	0.50	3502	5663	5943
		0.75	3289	5324	5568
		1.00	2874	3992	4086
		1.25	2462	3789	3872

tively for SFRC, GFRC and PFRC. It can also be observed that maximum loss of compressive strength due to the use of RCA + RFA is about 17% for SFRC, GFRC and PFRC (Table 2). Thus, the loss of compressive strength in FRC due to recycled aggregates is in the comparable range of that in PCC. Hence, it can be concluded that recycled aggregates can be beneficially used even in fibre reinforced concrete mixes also.

Split tensile strength: The split tensile strengths of all FRRAC mixes were considerably higher than that of plain concrete at all volume fractions. For mixes with steel fibres prepared with RCA at volume fraction of 1.25%, a maximum increase of 50.9% was recorded over plain concrete mix prepared with RCA. Similarly, the increase in split tensile strength for mixes containing glass fibres and polypropylene fibres were in the order of 39.8% and 44.4% respectively over plain concrete mixes. The increase in tensile strength due to the addition of fibres is expected because of the crack arresting and crack deflection mechanisms of fibres. Also, it is observed that mixes containing steel fibres have higher tensile strength when compared to that of glass fibre and polypropylene fibre mixes. The split tensile strength of all fibrous concrete mixes prepared with NA, RCA or RCA + RFA increases with the increase in the fibre volume. For illustration, the variation of split tensile strength of PFRC with fibre volume fraction is presented in Fig. 4. It can be observed that the maximum split tensile strengths were for mixes prepared with NA followed by mixes prepared with RCA and RCA + RFA. It can also be observed that the split tensile 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 fibre reinforced concrete mixes also.

Fig. 2: Test setup for shear strength.

Flexural strength: The flexural strength results of the present investigation are presented in Table 1. The flexural strengths of all fibrous concrete mixes were considerably higher than that of PCC. The flexural strengths were observed to increase with increase in fibre volume fraction in the ranges tested with maximum flexural strengths being achieved at 1.25% of fibre volume fraction. When compared to reference concrete PCC, the increase in flexural strength is in the range of 17.9 to 45.1%, 14.4 to 36.2%, and 16.2 to 41.5% respectively for SFRC, GFRC and PFRC prepared using natural aggregates (NA). Similarly for SFRC, GFRC and PFRC prepared using RCA, the increase in flexural strengths are in the ranges of 21.8 to 58.6%, 17.8 to 49.1%, 20.1 to 55.7% respectively. For SFRC, GFRC and PFRC prepared using RCA + RFA, the increase in flexural strengths are in the ranges of 23.9 to 58.9%, 20.2 to 50.2%, and 20.2 to 57.4% respectively. Maximum flexural strengths were contributed by the use of steel fibres, and minimum with glass fibres. Thus, it can be noticed that addition of fibres have considerably improved the flexural strengths of concretes prepared using recycled aggregates. As an example, the variation of flexural strength of GFRC with fibre volume fraction is presented in Fig. 5 for fibrous concrete mixes prepared with NA, RCA and RCA + RFA. It can be observed from this figure that for fibre volume fractions up to 0.75%, the difference between the flexural strengths of mixes prepared with RCA and RCA + RFA is very less. This trend is similar even for SFRC and PFRC mixes also. The maximum reduction in flexural strength due to RCA + RFA is 3.3%, 2.9% and 4.9% respectively for SFRC, GFRC and PFRC. Thus, the reduction in flexural strength due to RCA + RFA is observed to be marginal. Accordingly, the use of recycled fine aggregates in fibre reinforced concrete can be viewed as viable solution in saving the natural river sand.

Shear strength: From Table 1, it can be observed that the shear strength of all FRC mixes is considerably higher when compared to that of PCC. The increase in shear strength is in the range of 19.6% to 58.7%, 5.5% to 22.3% and 16.2% to 50.3% for SFRC, GFRC and PFRC mixes prepared with NA compared to corresponding PCC mixes. Similarly, for SFRC, GFRC and PFRC prepared using RCA, the increase in shear strengths are in the ranges of 20.7% to 74.4%, 7.3% to 30.7%, and 15.9% to 58.2% respectively. For SFRC, GFRC and PFRC prepared using RCA + RFA, the increase in shear strengths are in the ranges of 19.3% to 72.9%, 7.1% to 31.5%, and 17.6% to 58.0% respectively. Fig. 6 shows the percentage increase in shear strengths of FRC mixes compared to PCC at a fibre fraction of 1.25%. From this figure it can be observed that the maximum shear strengths were recorded for SFRC mixes, and minimum for GFRC for all types of aggregates tried. It can be noticed from Fig. 6 that the percentage increase in shear strength due to the addition of fibres is higher in mixes contain-

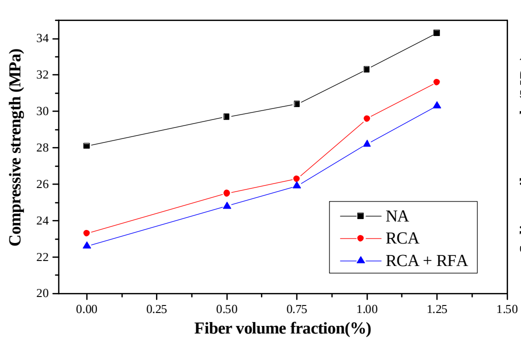

Fig. 3: Variation of compressive strength of SFRC.

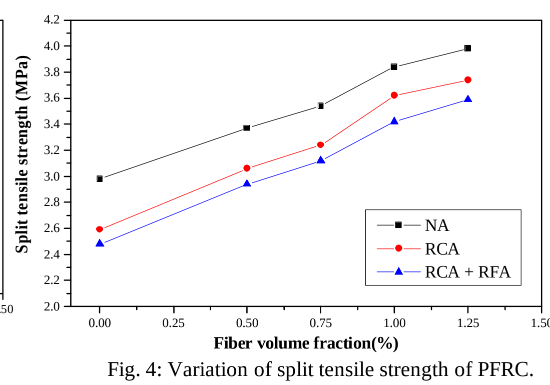

Fig. 4: Variation of split tensile strength of PFRC.

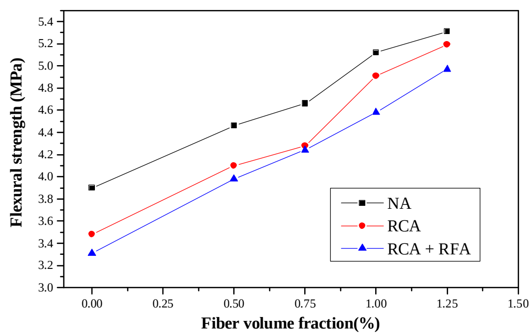

Fig. 5: Variation of flexural strength of GFRC.

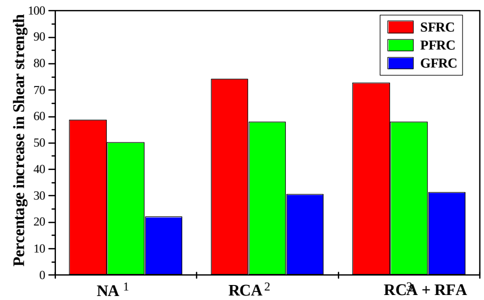

Fig. 6: Increase in shear strength for FRC at 1.25% as compared to PCC.

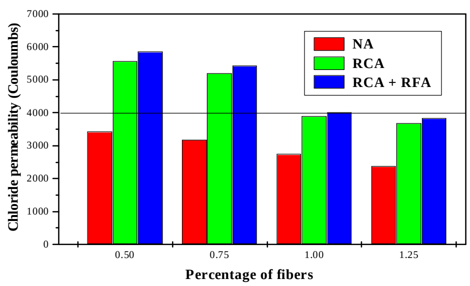

Fig. 7: Chloride ion permeability of SFRC mixes.

ing RCA or RCA + RFA when compared to NA. This is true for all the three types of fibre reinforced concretes prepared in this investigation. It can also be observed 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 fibre reinforced concrete mixes.

Chloride ion permeability: The results of chloride ion permeability tests conducted on various fibrous concrete mixes have been presented in Table 2. It can be observed that with increase in the fibre volume the chloride ion permeability decreases. This is true for all the three types of FRC mixes tried in this study. As an example, the variation of chloride ion permeability with fibre volume for SFRC mixes is presented in Fig. 7. From this, 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 aggregate is more porous when compared to that of natural aggregate, which is considered as impervious inert filler. 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 FRC mixes tried in this investigation. Hence, it can be said that recycled fine aggregate can safely be used in concrete works, thus, saving the usage of natural sand. It can also be observed that at fibre volumes of 1.00 and 1.25%, the chloride ion permeability values for FRC mixes prepared with RCA or RCA + RFA are falling below 4000 which is classified as moderate permeability range as per ASTM C-1202 classification presented in Table 3.

Table 3: 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

Thus, the addition of fibres is able to reduce the chloride ion permeability of mixes prepared with recycled coarse and fine aggregates below 4000 coulombs at 1.00 and 1.25 % volume fractions. It can also be observed from Table 2, that the chloride ion permeability values of FRC mixes prepared with RCA or RCA + RFA are almost comparable to the chloride ion permeability values of PCC at volume fractions of 1.25%. This indicates that RCA or RCA + RFA can be safely used in production of durable FRC.

CONCLUSION

Maximum compressive, tensile, flexural and shear strengths for fibre reinforced recycled aggregate concrete are recorded at fibre volume fractions of 1.25% in the ranges tested. Steel fibres contributed the higher strengths when compared to glass and poly propylene fibres. The compressive strength of FRRAC is found to increase with the increase in fibre content. The split tensile strengths of FRC mixes increase with the increase in fibre content for all the mixes prepared with NA, RCA or RCA + RFA. Considerable improvements in flexural strengths were noticed due to the addition of fibres to concrete mixes prepared with recycled coarse and fine aggregates.

Significant increase in shear strength has been recorded due to the addition of fibres to the concrete mixes prepared with recycled coarse and fine aggregates. It is observed that the percentage increase in shear strength due to addition of fibres is higher in mixes containing RCA or RCA + RFA when compared to NA. The chloride ion permeability of FRRAC mixes decreases with increase in fibre content. Addition of fibres in the ranges 1.0-1.25% decreases the chloride ion permeability well below 4000 coulombs even for mixes prepared with recycled coarse and fine aggregates which is classified as moderate permeability as per ASTM-C 1202 and can be safely adopted.

From both, strength and permeability characteristics, it is concluded that recycled coarse and fine aggregates can be safely used in the production of FRC mixes.

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