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ORIGINAL CONTRIBUTION

Effect of Fly-Ash on Corrosion Resistance Characteristics of Rebar Embedded in Recycled Aggregate Concrete

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Abstract In the frame of an extended research programme dealing with the utilization of recycled aggregate in concrete, the corrosion resistance characteristics of rebars embedded in recycled aggregate concrete is studied. Totally five series of concrete mixtures were prepared with fly-ash as replacement for cement in the levels of 10–30% by weight of cement. Corrosion studies by 90 days ponding test, linear polarization test and impressed voltage tests were carried out, in order to investigate whether corrosion behaviour of the rebars has improved due to the replacement of cement with fly-ash. Results showed that the replacement of cement with fly-ash in the range of 20–30% improves the corrosion resistance characteristics of recycled aggregate concrete.

Keywords Compressive strength · Corrosion · Fly-ash · Waste management · Recycled aggregate

Introduction

Recycling of concrete is needed from the viewpoints of environmental preservation and effective utilization of resources. The concept of sustainable development includes, first and foremost, the judicious use of natural resources, which in some areas are rapidly depleting. The possible use of recycled aggregates (RA) derived from construction and demolition (C&D) wastes have received increasing interest due to its potential to be used in environmentally friendly concrete structures. Secondly, it is necessary to reduce energy consumption that is associated with carbon dioxide and other greenhouse gas emissions [1]. The production of Portland cement also releases large amounts of carbon dioxide and other greenhouse gases to the atmosphere. For this reason, mineral admixtures such as fly-ash, silica fume (SF), metakaolin (MK) and Ground granulated blast furnace slag (GGBFS) have been utilized for many years as supplementary cementitious materials. These supplementary cementitious materials are being used in concrete and its use would help to achieve sustainability in the construction industry [2–6]. Generally, due to their high pozzolanic activity, the inclusion of MK and SF improves the mechanical and durability properties of the concrete [7–13].

The use of GGBFS as a partial replacement of ordinary Portland cement improves strength and durability of the concrete by creating a denser matrix and thereby would increase the service life of the concrete structures [14, 15]. It is well known that the incorporation of fly-ash and GGBS with normal fineness reduces the early strength of concrete, but they have long term advantages, such as improved long-term strength and durability, increased workability, reduced permeability and porosity, and reduced alkali-silica reaction expansion [16–19].

The issue of recycling rubble from C&D waste and their potential benefits and drawbacks of using RA in concrete have been extensively studied by many researchers [20–28]. Many studies have shown that using RA in concrete suffers from durability problems such as increased shrinkage and increased water absorption. [29–37]. Cui et al. [38] reported that the carbonation level of recycled aggregate concrete (RAC) is 3 times that of the natural aggregate concrete (NAC). Crentsil et al. [39] and Levy Salomon and Helene's [40] experimental results showed

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that, after 6 months of curing, the carbonation depth of the RAC was 1.3–2.5 times higher than that of the NAC. Otsuki et al. [41] reported that the resistance of RAC to chloride ion penetration and carbonation were slightly inferior to those of NAC given the same water-binder ratio was used. In a study carried out by Olorunsogo and Padayachee [31], it was found that the concrete mix containing 100% recycled aggregates showed a 73.2% increase in chloride conductivity at a curing age of 28 days. The negative effects of RA on concrete quality limit the use of this material in structural concrete. However, it has been suggested that the shortcomings of using RA can be mitigated by using the double mixing approach in concrete mixing, particularly for concrete prepared with high water-binder ratio, as it has been demonstrated that this improves the strength, chloride penetration, and carbonation resistances of RAC [42, 43]. Kou and Poon [44] evaluated the effects of poly vinyl alcohol (PVA) impregnation on the development of strength and durability properties of RAC and showed that there was not only an improvement in the mechanical properties of the PVA impregnated RAC, but also the shrinkage decreased, while the resistance to chloride-ion penetration increased. The application of these treatment techniques have significant impact on the environment, in terms of production of free chloride ions, energy involved etc. However, Grabiec et al. [45] investigated on the surface modification of recycled aggregate concrete using bio-deposition involving Bacillus pasteurii bacteria and obtained improved quality of RA.

Abbas et al. [46] also have demonstrated that by using an equivalent mortar volume method, RAC mixes have higher resistance to freeze–thaw action, chloride penetration and carbonation than those designed with the conventional method. It has also been shown that negative effect of RA can be mitigated by incorporating a certain amount mineral admixtures [47–53]. Recently Kou et al. [50, 51] found that when Class F fly-ash was used as an additional or cement replacement in the mixes, it can improve the mechanical and durability properties of RAC. While, most of the existing work is mainly carried out on RAC with the range of partial substitutes of RA along with fly-ash, Coninalsesi and Moriconi [52] have studied the strength and performance of 100% recycled aggregate for both coarse and fines. Their experimental results reveal that strength value of 30-35 MPa could be produced with RA and fly-ash.

In order to reduce the maintenance cost of reinforced concrete structures, the concrete cracking must be carefully dealt, in particular for reducing the risk of steel reinforcement corrosion. Extensive research work has already been performed on the use of fly-ash and other supplementary cementitious material as corrosion inhibitor of concrete material [54–62]. However, most of the existing

Table 1 Properties of fine aggregate

| S. no.	Test properties	Results
1	Specific gravity	2.56
2	Fineness modulus	2.805
3	Bulk density (kg/m^3)	1655 kg/m^3
4	Water absorption (%)	1%
5	Moisture content (%)	0.6%
6	Zone	II

work is mainly carried out on concrete with NA and only limited studies are reported in literature on corrosion studies related to RAC [63–65]. Hence, the current investigation attempts to study the corrosion inhibition characteristics of RAC with 100% RA as coarse aggregate with fly-ash as partial cement replacement for cement.

Experimental Investigations

Materials Used

Ordinary Portland cement of 43 grade confirming IS 8112-1989 [66] was used for the present study. Class F fly-ash obtained from Neyveli Thermal power plant is used for as replacement for cement. Locally available river sand is used as fine aggregates whose properties are determined as per IS 383-1970 [67] and the results are presented in Table 1.

Both natural aggregate (NA) and recycled aggregate (RA) were used as the coarse aggregate in the concrete mixtures. Crushed granite obtained from the local quarry was used as NA. The crushed concrete specimen waste available in the laboratory is used as the source of RA. The compressive strength of these parent concrete chunks is about 30–50 MPa. These concrete chunks were crushed manually and subsequently crushed with a lab model jaw crusher and sieved. The aggregate passing in 20 mm sieve and retained on 4.75 mm sieve is used as RA. RA has some old mortar adhered on its surface. Though there is no authentic information available to support that the virgin aggregates in NA and RA are from the same quarry, it is highly probable, as there is only one quarry situated in the near vicinity of the study area. The nominal size of NA and RA was 20 mm and their particle size distributions determined as per IS 383-1970 [67] are shown in Fig. 1. The physical and mechanical properties of NA and RA were determined in accordance with IS 2386-1963 [68] and presented in Table 2. Potable water available in the college campus was used for making concrete. Super plasticizer Supaflo was also used at 0.75% (of cement by weight), in order to make the concrete mixture workable.
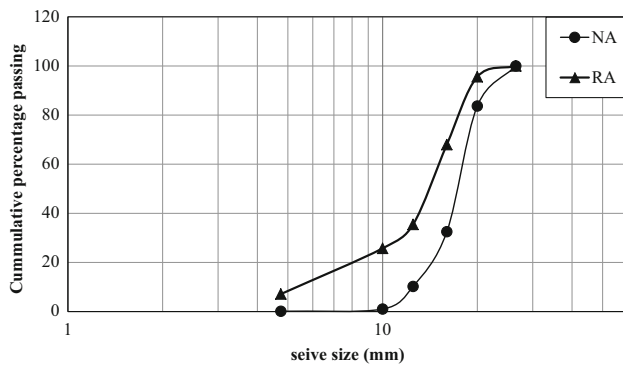
Fig. 1 Particle size distribution curve for coarse aggregate

Table 2 Properties of coarse aggregate

Properties	Test results	
	NA	RA
Specific gravity	2.68	2.43
Water absorption (%)	0.5	1.56
Bulk density (kg/m³)	1508	1239
Aggregate crushing value (%)	14.2	17.69

Mixture Proportioning

A mix was proportioned with conventional materials for a characteristic strength of 25 MPa as per IS 10262-2009 [69]. The mix proportion was arrived as 1(cement): 2.15(sand): 2.86 (coarse aggregate) with water cement ratio as 0.45 and cement content of 380 kg/m³. A concrete mix was prepared in the above proportion using conventional ingredients such as natural coarse aggregate and natural fine aggregate for reference and designated as natural aggregate concrete (NAC). Another concrete mix was prepared in the same proportion replacing NA completely with RA and designated as RAC. In order to assess the effect of fly ash on corrosion characteristics of RAC, corrosion studies were planned and conducted on fly-ash added concrete. In the RAC series of concrete mixtures, the cement was replaced by weight with fly-ash by 10, 20 and 30% and designated as RAC10, RAC20 and RAC30 respectively. The numeral in the mixture designation

denotes the replacement levels of cement with fly-ash in the concrete mixtures. The water to the binder (cement + fly-ash) ratio of these mixes are maintained as 0.45 as that of reference concrete. The constituents of various mixtures are given in Table 3.
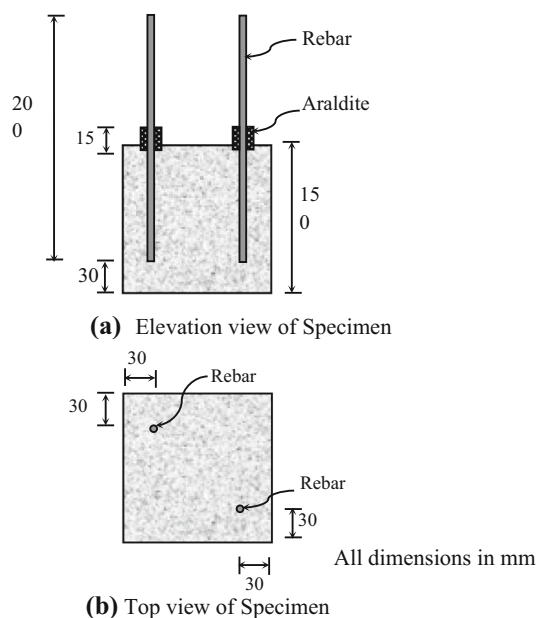
Investigation Methods

Cube specimens, 100 mm size, were made in order to obtain compressive strength for each mixture at 14, 28 and 56 days of age. Automatic compression testing machine of capacity 3000 kN was used for testing the compressive strength of specimens. The test specimens were placed at the centre of the loading platform and tested under axial compression without any eccentricity.

The following electrochemical techniques were performed on all reinforced concrete specimens, in order to study the corrosion process and the effect of the replacement of cement with fly-ash in RAC.

Ponding Test

90 days chloride ponding test as cited by Vedalakshmi et al. [55] was conducted with all the concrete mixtures. In order to conduct, ponding test, cube specimens of 100 mm size were cast after placing two numbers of 10 mm diameter reinforcement bars (rebars) of 200 mm length. The rebar was embedded inside the specimen for 100 mm inside at a clear cover of 30 mm from sides. The rebar was pickled in inhibited hydrochloric acid solution in order to remove the initial rust present on the surface of the specimen. Each rod was sealed with araldite sealant to height of 15 mm at the level of the specimen, in order to arrest the ingress of ponding solution directly into the rods. The schematic representation of the specimen is shown in Fig. 2. These specimens were cured for 28 days under laboratory conditions and air dried for 1 day. Bunds were constructed over the cubes as shown in Fig. 3 using PVC pipes. Sodium Chloride solution of 3% concentration was ponded to a height of 70 mm above the specimens. One rebar was connected to the positive terminal and the other rod was connected to the negative terminal of the battery and a constant voltage of 23 V DC was supplied. The

Table 3 Mix constituents (kg/m³)

Mix designation	Coarse aggregate	Fine aggregate	Cement	Fly-ash
NAC	1087	820	380	0
RAC	1047	820	380	0
RAC10	1047	820	342	38
RAC20	1047	820	304	76
RAC30	1047	820	266	114

(a) Elevation view of Specimen

(b) Top view of Specimen

All dimensions in mm

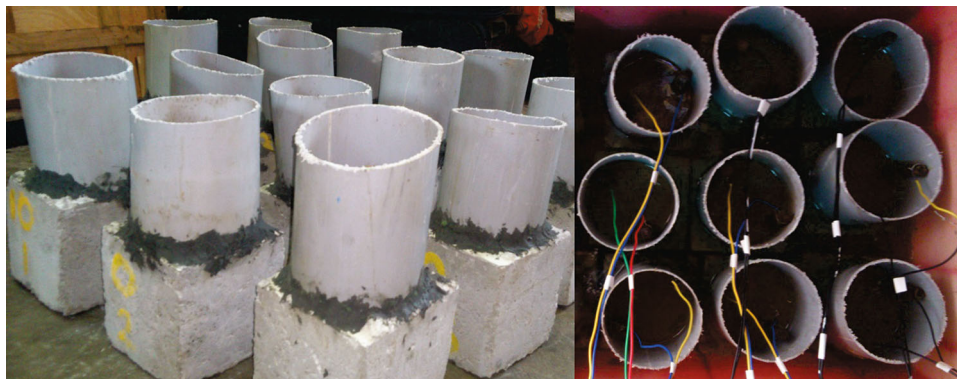Fig. 2 Schematic representation of specimen for ponding test

current in mA and polarisation resistance in ohms were noted at 24 h interval till 90 days using a micro ammeter and multi-meter respectively. The corrosion current (i_{corr}) and corrosion rate are evaluated using the Stern–Geary equation

$$i_{corr} = \frac{B}{R_p} \qquad (1)$$

Corrosion rate $(mmpy) = 0.0116 \times i_{corr} \qquad (2)$

where B is the Stern–Geary Constant. Conventionally, the value of B for steel–concrete systems is regarded within the range between 25 and 52 mV and $B = 26$ mV is usually assumed [55] and R_p is the Polarization resistance in ohms per unit area of cross section of rebar.
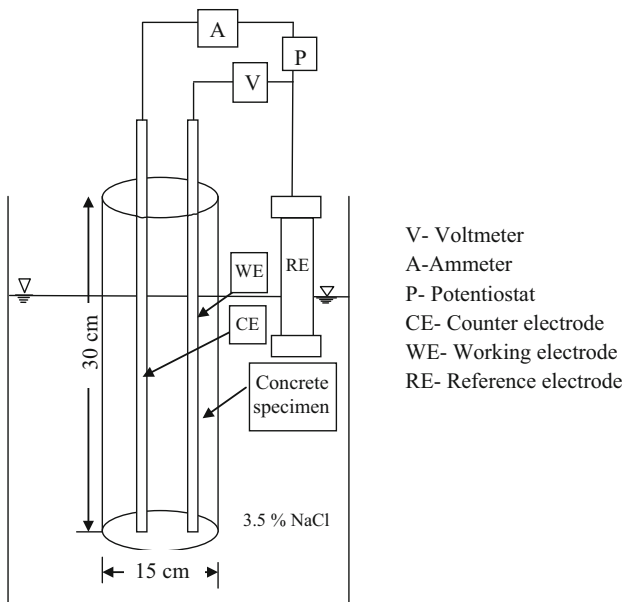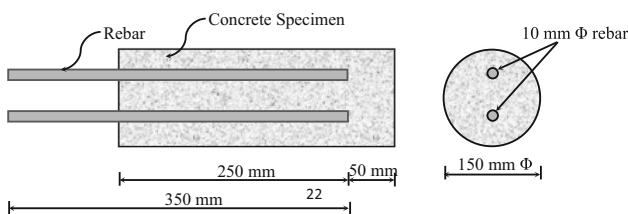
Linear Polarization Resistance (LPR) Test

The schematic representation of the corrosion measurement with the test specimen is shown in Fig. 4. Cylinder specimens of 100 mm diameter and 300 mm height were cast in each series of concrete mixtures. Each specimen was embedded with two numbers of 10 mm diameter rebars with an embedment length of 250 mm inside at a clear cover of 50 mm from the bottom of the specimen as shown in Fig. 5. These specimens were cured for 28 days under laboratory conditions and air dried for 1 day. Specimens were kept in 3.5% NaCl solution and one rebar was connected to the positive terminal and the other rod was connected to the negative terminal of the battery and a constant voltage of 12 V DC was supplied. A similar impressed-voltage test setup has been reported by other researchers [56, 70]. The current flow between the rebars in mA was noted down at every 24 h interval. The resistance of charge transfer (R_{ct}), which has correlation with the corrosion current density (i_{corr}) of the rebar are also measured, with standard calomel rod as reference electrode [56, 70].

Impressed Voltage Test

The reinforced concrete specimens for the impressed voltage tests were the cylinder specimens with the dimensions of 150 mm × 300 mm, in which a 10 mm diameter rebar is centrally embedded to a depth of 250 mm as shown in Fig. 6. The specimens were demoulded after 24 h and immersed in water for curing. The impressed voltage tests were carried out after 28 days of curing. The setup for this test includes a DC power source, a plastic tub containing a 4%-NaCl solution, test specimens with rebar embedded inside, which acts as anode and stainless steel rod acting as cathode. All the specimens were subjected to a constant voltage of 24 V DC during the test period. This impressed-voltage test setup used for the present study is shown in Fig. 7. A similar impressed-voltage test setup with the same test conditions have been reported by other

Fig. 3 Specimens under ponding

Fig. 4 Schematic representation of typical corrosion measurement set-up test

V- Voltmeter
A-Ammeter
P- Potentiostat
CE- Counter electrode
WE- Working electrode
RE- Reference electrode

Fig. 5 Schematic representation of specimen for LPR test

researchers [56, 70–72]. The voltage passed was regularly checked and the specimens were keenly investigated for visual cracks. The number of days required to initiate visible crack was noted.

Weight Loss Test on Rebars

Weight loss test enables us to assess the quantity of rebar, which has been corroded during the experiment. It is obtained by noting the difference in the initial and final weights of the rebar used in the above corrosion studies and expressed as percentage of initial weight. After completion
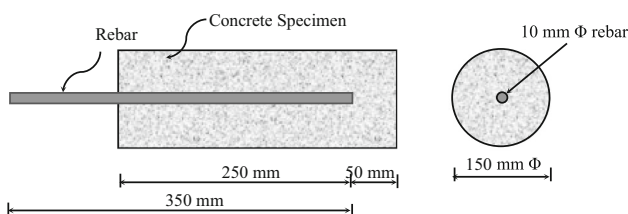
Fig. 6 Schematic representation of specimen for impressed voltage test

Fig. 7 Experimental setup for impressed voltage test

of each experiment, the rods were taken out and cleaned with hydrochloric acid solution and final weight was noted to evaluate the percentage loss of weight in rebars. This test is carried out in accordance with the literature reported by Boga et al. [72].

Results and Discussion

The results of the experimental investigations carried out as part of the present research study are discussed in the following section, with a special emphasis on the possible synergic effects induced by combining RA and fly-ash in concrete mixtures.

Properties of Recycled Aggregate

The specific gravity (saturated surface dry condition) of RA was found to be 2.43, which is lower than the specific gravity of natural aggregates of 2.68. The water absorption of NA and RA are 0.5 and 1.56% respectively. The bulk density of RA was also found to be lower than that of NA. The main factor affecting specific gravity, water absorption and bulk density of RA is the old mortars adhering to it. A lower percentage of aggregate crushing value indicates tougher and stronger aggregates. From the results, it is observed that the crushing value of NA and RA is 14.2 and 17.69% respectively. It is clear that, the resistance against crushing of RA is relatively lower than NA, due to the separation and crushing of porous mortar coating present on it.

Workability of Fresh Concrete

Slump tests have been performed for determining the consistency of all the produced concrete batches, thus evaluating the influence of the combined use of RA and fly-ash on the workability of fresh concrete mixtures. The
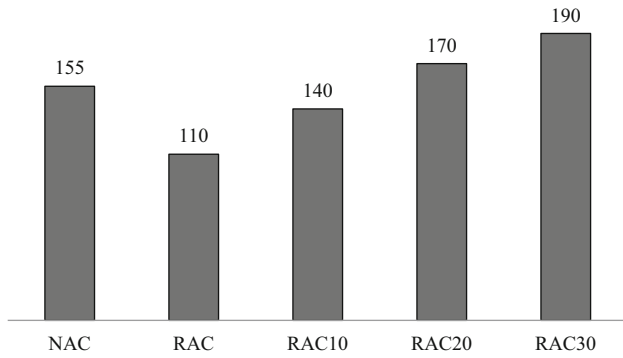
Fig. 8 Measured slump values (mm)

Fig. 10 Measured curent values in ponding test

reference concrete mixture NAC has been designed to achieve a slump of 100–150 mm: for this reason a small quantity of a super plasticizer (0.6% by weight of cement) was added. Results from slump test are shown in Fig. 8. From the results of slump test the following observation can be drawn: (1) the desired slump have been obtained for the reference mix NAC. (2) Due to the rougher surfaces and to the more irregular shapes of RA with respect to NA, the replacement of NAs with RAs has caused a significant reduction in workability. (3) On the other hand, the addition of fly-ash in the mixture has produced clear increase in slump.

Compressive Strength

Figure 9 reports the average values of the compressive strength evaluated by testing three cube samples of all the concrete mixtures under consideration. The 28 day compressive strength of NAC is 34.5 N/mm^2 while the compressive strength of RAC is only 28.21 N/mm^2. This major reduction is due to the complete replacement of NA with RA, which weakens the inter facial transitional zone in the aggregate cement matrix, due to the presence of old mortar attached on it. With the adequate replacement of cement
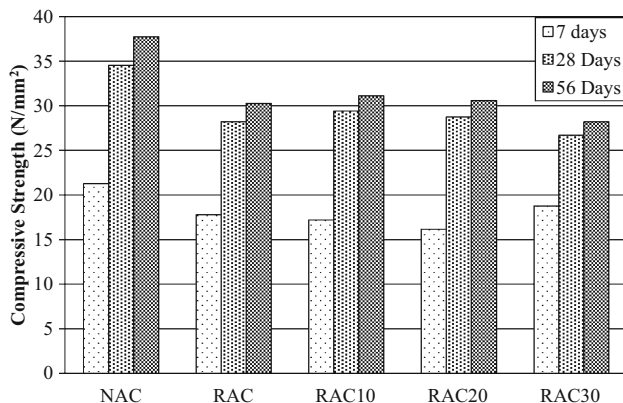
Table 4 Comparison of corrosion resistance properties of various concrete mixtures
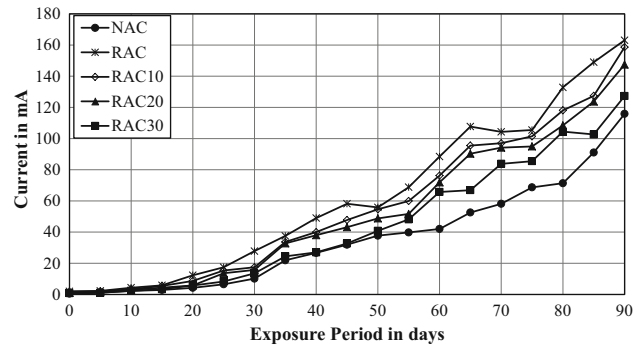
| Mix series	Corrosion rate (mmpy) from ponding test	
	Initial	At 90 days of exposure
NAC	0.0098	0.0207
RAC	0.0169	0.0661
RAC10	0.0102	0.0376
RAC20	0.0108	0.0222
RAC30	0.0116	0.0246

with fly-ash in RAC, the 28 day compressive strength is marginally enhanced. However, with the replacement levels beyond 20%, the compressive strengths both at 28 and 56 days of age could not be enhanced.

Ponding Test Measurements

From the ponding test, the corrosion potential of concrete in terms of current in mA was recorded and plotted against time in days and shown in Fig. 10. It is clear from Fig. 10 that, the measured current values, which are the indicators of corrosion rate, is lower in NAC whereas maximum current is recorded in RAC at all exposure periods. This is clearly due to the poor quality of RA and the attached mortar on it. However, the current values are better controlled with the fly-ash as replacement for cement. It is seen that the corrosion currents are lower as the level of fly-ash replacement moves from 10 to 30%. This reduction in current rate is attributed to the fine nature of fly-ash and its pore filling ability in concrete structures. Table 4 compares the initial and final corrosion rates of rebars embedded in various concrete mixtures. It is evident that, the rebar in NAC shows initial corrosion rate value of 0.0098 mmpy which increases to 0.0207 mmpy at the end of 90 days. The corrosion rate is 0.0661 mmpy for RAC at the end of 90 days which is almost 4 times its initial value. Initially the rebar in all the five concretes show more or less same

Fig. 9 Compressive strength of concrete mixtures

Fig. 11 Damaged specimens with rebars after linear polarisation test
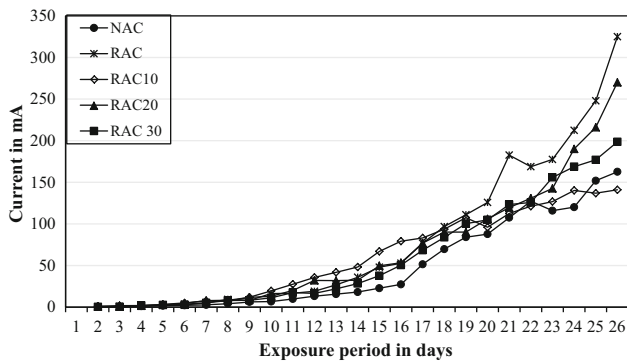
Fig. 12 Measured current values from LPR test

Fig. 14 Damaged specimens with rebars after impressed voltage test

Table 5 Damage occurrence time of various samples from impressed voltage test

mix series	Damage occurrence time in hours
NAC	442
RAC	374
RAC10	438
RAC20	462
RAC30	478

corrosion rate whereas at the end of 90 days, the rebar in RAC shows up to 3 times higher rate than that of NAC. With the replacement of cement with fly-ash, the corrosion rate at the end of 90 days in all the recycled aggregate concrete mixtures is found to be decreased remarkably.

LPR Test Measurements

The damaged specimens and measured current in mA for various concrete mixtures is shown in Figs. 11 and 12 respectively. According to Fig. 12, the corrosion currents
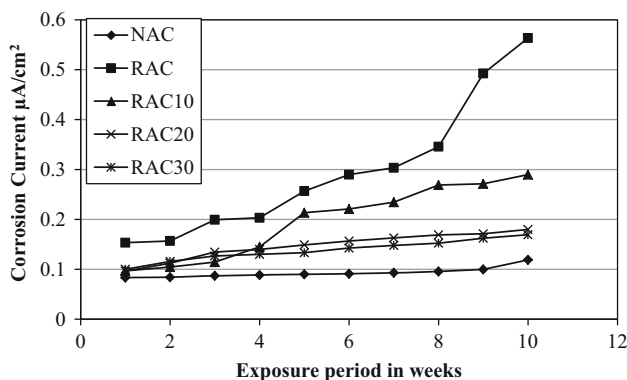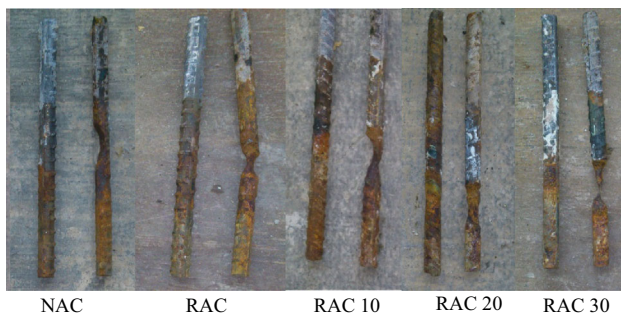

Fig. 13 Corrosion current density from LPR test

increase with time and it is seen that some series have sudden increases. During the initial periods there was not much difference in the currents in various concrete mixtures, which means that fly-ash does not contribute significantly to inhibit the corrosion of the reinforcement. The negligible effect of fly-ash on corrosion current density at initial days is mainly attributed to the delay of the kinetics of texturing of the cementing paste due to the slowness of the pozzolanic reaction of the fly-ash with Calcium hydroxide. However, roughly after 14 days of exposure, the rebars in mix series NAC gave lowest current values, while the rebars in mix series RAC gave larger current values indicating its higher potential for corrosion. This similar trend is witnessed at all the remaining exposure periods. Better test results are achieved with the replacement of cement with fly-ash. It is seen that, the corrosion current of the specimens is reduced by using the fly-ash as replacement from 10 to 30%. RAC10 is having less corrosion rate and is approximately equal to that of NAC.

The corrosion current density for various concrete mixtures is shown in Fig. 13. The corrosion level is considered negligible when corrosion current density i_{corr} is less than 0.1 μA/cm^2, while it is considered low to moderate corrosion in the range between 0.1 and 0.5 μA/cm^2, high in the range between 0.5 and 1 μA/cm^2 and very high for values superior to 1 μA/cm^2 [56]. Figure 13 indicates that the corrosion current density of NAC is less than

Fig. 15 Corroded rebars taken out from specimens of ponding test

Fig. 16 Corroded rebars taken out from specimens of linear polarization test

0.1 µA/cm^2, denoting negligible corrosion level, whereas the corrosion current density of RAC is between 0.15 and 0.56 µA/cm^2, denoting moderate range of corrosion. This is attributable to the attached mortar on the surface of RA, which makes RAC more porous and hence more susceptible for corrosion. The corrosion current density rapidly rose for RAC after 8 weeks of exposure. With the replacement of cement with fly ash, the corrosion current density of RAC mixtures were brought down. It is evident from Fig. 12 that the corrosion inhibition potential of rebars in RAC20 and RAC30 are much close to NAC.

Impressed Voltage Test Measurements

After the impressed voltage tests, steel in the reinforced concrete corroded and the specimens were damaged. The damaged specimens are shown in Fig. 14. Since the volume of the corrosion products (rust) are 2.5–6 times greater than the volume of the steel used in the concrete, these corrosion products lead to higher internal tensile stresses in

the hardened concrete. These concrete specimens, being exposed to these stresses, the hardened concrete cracks and splits off. This damage occurrence times (DOTs) of the accelerated-corrosion specimens are shown in Table 5. As seen in Table 5, the DOT ranges between 374 and 472 h. According to Table 5, as is the case with RA specimens, replacement of cement with fly-ash leads to a longer DOT. With respect to DOTs, it is observed that the best results are obtained for the specimens produced with RA and 30% fly-ash. The results of the impressed voltage test also add to the justification for replacing cement with fly-ash in RAC for improving upon its corrosion resistance characteristics.

Loss of Weight on Rebars

The Figs. 15, 16 and 17 show the corroded rebars taken out of the damaged samples after Ponding, Linear Polarization and Impressed Voltage tests respectively. The weight losses of the steel reinforcements in various concrete mixtures that were exposed to corrosion are shown in Table 6. According to a general assessment of these, the weight loss is seen to decrease as the amount of fly-ash, being the replacement of the cement is increased. As it is seen in Table 6, the maximum weight loss is observed with the concretes that did not have any fly-ash but produced with RA. The weight losses decrease as the amount of fly-ash increases in the concretes. It is observed from Table 6, that the optimum replacement level for fly-ash in cement seems to be 20% for better performance of rebars in terms of its corrosion resistance characteristics.

Conclusions

After the tests, it was observed that the mechanical properties of concrete and corrosion performances of the steel rebars embedded in concrete changed with the quantity of cement replaced with fly-ash. In addition to the above, the following salient conclusions are drawn, based on this limited experimental study.
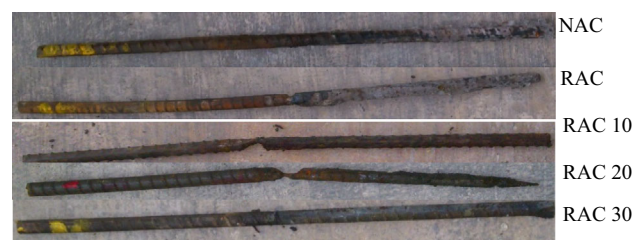
Fig. 17 Corroded rebars taken out from specimens of impressed voltage test

Table 6 Percentage weight loss of rebars embedded in various concrete mixtures

Mix series	Salt ponding test	Linear polarization test	Impressed voltage test
NAC	4.09	7.4	8.14
RAC	7.8	10.3	14.5
RAC10	5.6	7.6	10.13
RAC20	4.54	8.1	9.6
RAC30	6.21	7.4	11.14

1. Quality of recycled concrete aggregate in terms of specific gravity, water absorption, bulk density and crushing value, is lower than natural aggregate, due to the mortar that remains attached on the surface of it.
2. Replacement of cement with fly-ash improved the workability of fresh concrete within 10–30% replacement levels. The compressive strength of RAC is 18–20% less than NAC at 28 days of age.
3. Results of Salt Ponding test showed that replacement of cement in RAC with fly-ash in the range of 10–30% improved upon the corrosion resistance potential of rebars embedded in it.
4. The corrosion current obtained from LPR test of RAC containing fly-ash is lower, indicating the lower levels of corrosion in RAC20 and RAC30. These corrosion current values are closer to NAC.
5. According to the general assessment of the results, an increase in the replacement level of cement with fly-ash caused increase in damage occurrence time of reinforced concrete specimens.
6. With respect to the assessment of corrosion rate, corrosion current, damage occurrence time and loss of weight on rebars, the most positive results were observed with the RAC specimens that were produced with 20–30% fly-ash as replacement for cement.
7. To combat the corrosion of steel reinforcement in RAC, the permeability of concrete by water and hazardous ions have to be prevented. This is possible by producing an impermeable concrete. For this reason, impermeable and high quality RAC corrosion resistance on par with NAC can be produced by using 20–30% fly-ash as replacement for cement in it.

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