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Durability characteristics of recycled aggregate concrete

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Abstract. People started to replace natural aggregate with recycled aggregate for a number of years due to disposal problem and certain other potential benefits. Though there are number of drawbacks with use of recycled aggregates like lesser modulus of elasticity, low compressive strength, increase in shrinkage, there are results of earlier studies that use of chemical and mineral admixtures improves the strength and durability of recycled concrete. The use of recycled aggregate from construction and demolition wastes is showing prospective application in construction as alternative to natural aggregates. It conserves lot of natural resources and reduces the space required for the landfill disposal. In the present research work, the effect of recycled aggregate on strength and durability aspects of concrete is studied. Grade of concrete chosen for the present work is M50 (with a characteristic compressive strength of 50 MPa). The recycled aggregates were collected from demolished structure with 20 years of age. Natural Aggregate (NA) was replaced with Recycled Aggregate (RA) in different percentages such as 25, 50 and 100 to understand its effect. The experiments were conducted for different ages of concrete such as 7, 14, 28, 56 days to assess the compressive and tensile strength. Durability characteristics of recycled aggregate concrete were studied with Rapid chloride penetration test (as per ASTMC1202), sorptivity test and acid test to assess resistance against chloride ion penetration, capillary suction and chemical attack respectively. Mix design for 50 MPa gives around 35 MPa after replacing natural aggregate with recycled aggregate in concrete mix and the chloride penetration range also lies in moderate limit. Hence it is understood from the results that replacement of NA with RA is very much possible and will be ecofriendly.

Keywords: natural aggregate; recycled aggregate; recycled aggregate concrete; compressive strength; tensile strength; Rapid chloride penetration test (RCPT); Sorptivity test

1. Introduction

Reuse of crushed aggregates from construction and demolition wastes as substitute for natural aggregates is very much beneficial from the point of protecting natural resources and environment. Many research works were carried out so far to investigate the possibility of using recycled aggregate as coarse aggregate. None of the previous results indicated that the recycled aggregate concrete was unsuitable for structural applications. This paper presents the experimental results of various percentage replacements of NA with RA and results are compared with the natural aggregate concrete.

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Dhir *et al*. (1998) performed an experimental program on use of RA in concrete and found that NA replacement up to 30% will not have significant adverse effects on recycled aggregate concrete (RAC) cube strength. For higher NA replacement with RA, some modifications in mix design may be needed to ensure the equivalent performance of natural aggregate concrete. Yamato *et al*. (1998) studied the possibility of replacing 30%, 50% and 100% of NA with RA and found that there was 20%, 30% and 45% decrease in compressive strength of RAC respectively for three different cases. Poon *et al*. (2007) studied the effect of shape and surface characteristics of RA and found that angular shape and rough surface leads to better bond and higher strength of RAC. They also suggested that recycled aggregates should be oven dried to improve the compressive strength.

Rahal (2007a, b) investigated the mechanical properties of recycled aggregate concrete with a compressive strength ranging from 20 to 50 MPa and compared their results with NAC. He found that only 10% difference was observed between RAC and NAC in terms of compressive strength, indirect shear strength and modulus of elasticity. Evangelista and de Brito (2007) found that 30% replacement of the fine natural aggregates with recycled aggregates did not jeopardize the strength. It was also shown that blends of 50% natural and 50% recycled sands produced strengths up to 20% less than recycled concrete made with all natural sands. Yong and Teo (2009) studied the possibility of utilizing RA as coarse aggregate in concrete and they tried with three types of aggregates such as natural coarse aggregate, natural fine aggregate and recycled coarse aggregate and found that RAC gives better results than NAC in terms of compressive strength and split tensile strength, whereas it shows reverse trend in flexural strength. Wang *et al.* (2012) reported the results of replacements for fine aggregates with recycled green building materials based on a Taiwan-made recycled mineral admixture in light weight aggregate concrete. Waste LCD glass sand and waste tire rubber powder were used as a replacer for fine aggregate as 5% and10% respectively. They concluded that the lightweight aggregate concrete has shown better hardened properties than normal-weight concrete and recycled green building materials can be used in lightweight aggregate concrete. Mirza and Saif (2010) studied the possibility of using RA with silica fume on concrete characteristics. NA was replaced with 0, 50 and 100% of RA and cement replaced with silica fume with 5, 10 and 15%. They found that use of 50% recycled aggregate is possible with 5% silica fume in structural concrete.

For concrete made with 100% RA, the compressive strength and modulus of elasticity of RAC was reportedly decreased at different percentages. For instance, Bairagi and Kishore (1993) reported 40% reduction in compressive strength, Ravindrarajah (2000) measured a 9 % decrease and Amnon (2003) reported 25 % reduction in compressive strength of concrete. Several other researchers (Tavakoli and Soroushian 1996, Sagoe *et al*. 2001) have reported that the tensile strength of RAC is similar or usually better than that of NAC concrete, which is contrast to the results of compressive strength and modulus of elasticity. Ajdukiewicz and Kilszczewicz (2002) found that the difference between tensile strength of RAC and reference concrete at 28 days was less than 10%. Park *et al*. (2013) proposed a new mix design method for recycled aggregate concrete. Genetic algorithm was used to develop this method. Several mix proportions were arrived using this approach and the fitness functions applied in this were developed based on earlier research reports. Saravanakumar and Dhinakaran (2012) studied the basic properties of RA with three different ages of five, ten and fifteen years. The results were compared with NA and they found that the properties of RA were comparatively poorer than the NA. But they found that the results were encouraging when the RA was replaced and used as a substitute of coarse aggregate in concrete.

The results reported in this paper examine the effect of recycled aggregate on strength and

Table 1 Chemical composition of materials used

Description	Aggregate (%)	RA (%)	Cement (%)
SiO_2	58.54	56.89	24.50
Al_2O_3	17.81	19.93	7.00
CaO	6.17	10.57	63.00
Fe_2O_3	6.07	4.15	0.55
Na_2O	4.2	3.85	0.40
MgO	2.91	1.92	2.00
K_2O	2.65	1.03	0.60
TiO_2	0.66	0.60	-
P_2O_5	0.38	0.48	-
BaO	0.15	0.20	-
SO_3	0.14	0.15	1.50
SrO	0.07	0.06	-
MnO	0.06	0.06	-
Cl	0.06	0.04	0.05
ZrO_2	0.06	0.02	-
Cr_2O_3	0.04	0.02	-
NiO	0.01	0.01	-
ZnO	89ppm	50ppm	-
Rb_2O	46ppm	79ppm	-

durability characteristics of concrete. Four types of mixes with different percentage of replacements of natural aggregates were prepared for the study. The first concrete mix was a control concrete, in which natural coarse aggregate was used. In the second concrete mix, 25% of the natural coarse aggregate was replaced with recycled aggregate, in the third concrete mix, 50% of the natural coarse aggregate was replaced with recycled coarse aggregate and in the fourth one 100% of the natural coarse aggregate was replaced with recycled aggregate. The influences of quantity of recycled aggregate on compressive and tensile strength were determined. Durability aspects like sorptivity, resistance against chloride ion penetration, alkalinity and chemical attack were also considered in the present study.

2. Experimental investigations

2.1 Material properties

Ordinary Portland cement of 53 grade was used in the present research work. River sand was used as fine aggregate and conformed to the standards of ASTM C 33. Broken stone was used as coarse aggregate. The specific gravity was 2.65 for river sand, 2.70 for broken stone and 3.12 for cement. Recycled aggregates were obtained from a demolished building with an age of 20 years. This information was obtained from the owner of the respective demolished building. After identifying the site for RA, the materials were collected through the truck in bulk quantity and were crushed to get segregate the aggregates. Adhered mortar was removed to the maximum

Table 2 Slump values for selected mix proportions

Mix Designation	Slump values in mm
NAC	88
25% RAC	85
50% RAC	82
100% RAC	78

possible extent from aggregate. The chemical composition of materials was done by X-ray fluorescence analysis using XRF spectrometer for the materials used in the present research work such as natural aggregate, recycled aggregate and cement are given in the Table 1.

2.2 Specimen details

Concrete mix design was done as per ACI method for M50 grade concrete to obtain a characteristic compressive strength of 50 MPa and the mix proportion arrived was 1:0.775:2.325 (Cement : Fine Aggregate : Coarse Aggregate) with 0.35 as its water cement ratio. Addition of super plasticizer (high range water reducer) reduces w/c ratio from 0.35 to 0.30. The values of slump obtained for different combination of mixes are given in Table 2.

The exact quantity of material for each mix was calculated and specimens were cast accordingly. For testing compressive strength, specimens of size 100 mm × 100 mm × 100 mm cubes were cast and for tensile strength cylinders with 100 mm diameter and 200 mm height were cast as per ASTM standard. Total of 48 numbers of concrete cubes were cast for testing compressive strength and 48 cylindrical specimens were cast for testing tensile strength. All the specimens cast for compressive strength was subjected to different period of curing such as 7, 14, 28 and 56 days. For short-term durability study, cylinders of 100 mm diameter × 50 mm height were cast for Rapid chloride penetration test (as per ASTM C1202) and sorptivity test. Concrete cubes of 100 mm × 100 mm × 100 mm were cast for finding the resistance against acid and sulfate attack (i.e., HCl and H_2SO_4).

2.4 Sorptivity test

The 100 mm × 50 mm Cylinder specimens were preconditioned by drying the sample for 7 days in a 50°C oven and then allowed to cool in a sealed container for three days. The sides of the concrete sample are sealed, typically with electrician's tape. The initial mass of the sample is taken and the sample is immersed to a depth of 5 mm in the water. At selected times (typically 1, 2, 4, 9, 16, 25, 30, 60, 90.120, 150, and 180 minutes) the sample is removed from the water, the stopwatch stopped, excess water blotted off with a damp paper towel and the sample weighed. It is then replaced in the water and the stopwatch started again. The gain in mass per unit area over the density of water is plotted versus the square root of the elapsed time. The slope of the line of best fit of these points (ignoring the origin) is reported as the sorptivity.

2.5 Rapid chloride permeability test

Rapid chloride penetration test was performed as per ASTM C1202 standards. The 100 mm

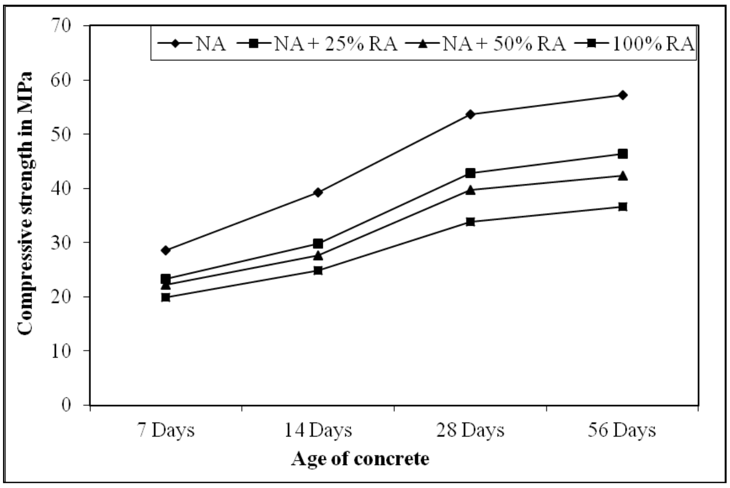

Fig. 1 Effect of RA on compressive strength

diameter × 50 mm length cylinder specimens were coated with epoxy and placed in the testing apparatus where one end of the specimen is exposed to a sodium chloride (NaCl) solution and the other end is exposed to sodium hydroxide (NaOH) solution. A constant 60 V potential current was applied and the current across the specimen was measured at every 30 minutes upto 6-hours.

2.6 Alkalinity and resistance against HCl and H_2SO_4

Compressive strength of concrete cube specimens of size 100 mm × 100 mm × 100 mm cured in water, 10% HCl solution and 10% H_2SO_4 solution for 28 days and were tested in automatic compression testing machine with a capacity 3000 kN. For alkalinity test the cured specimens were taken out and dried in an oven at 105° C for 24 hrs. The dry specimens were cooled to room temperature. Dry specimens were broken and samples were taken. The sample was ground and sieved in 150 µ sieve. 10 g of sample was taken and was diluted in 50 ml-distilled water and completely stirred. Then the pH meter was immersed into the solution and pH value of solution was noted.

3. Results and discussion

3.1 Compressive strength of RAC

The variation of compressive strength of concrete with respect to age due to the replacement of NA with different percentages of RA is shown in Fig. 1. From the results it is understood that control concrete gives compressive strength values of 28.5 MPa, 39.21 MPa, 53.21 MPa and 57.21 MPa at the ages of 7, 14, 28 and 56 days respectively. Replacement of NA with RA reduces strength irrespective of age. The rates of reduction were found to be 18.5%, 22% and 30% for 25, 50 and 100% replacement at the age of 7 days and were 24%, 29.5% and 36.5% respectively at the age of 28 days (Fig. 2).

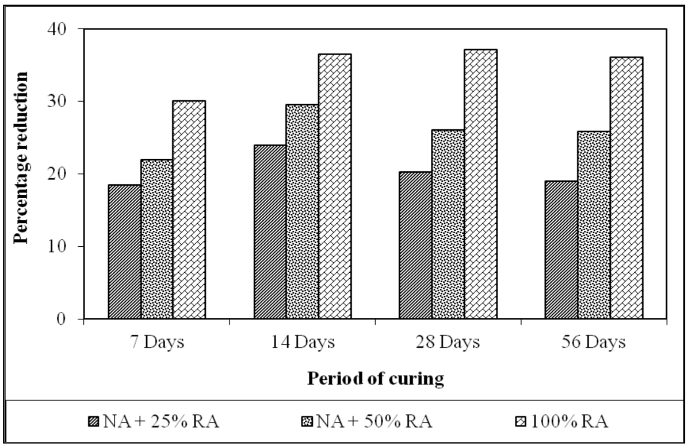

Fig. 2 Percentage reduction in compressive strength

At the age of 56 days the rate of reduction in strength was observed as 19%, 26% and 36% and was showing encouraging trend to use RA in the later age. From the above results it was very clear that RA could be used as ingredient in structural concrete with some modifications in mix design. Earlier researchers Poon *et al*. (2007) reported in their results that when 100% recycled aggregate was used; the compressive strength of concrete was reduced by about 24 %. Experimental results of Etxeberria *et al*. (2007) shown that the compressive strength of recycled aggregate concrete (with 25, 50 and 100% replacement) was increased by 12-15% more in the last 21 days of 28 days age. It may be due to rough texture and absorption of capacity of adhered mortar in recycled aggregate that develops better affinity and interlocking between cement and aggregate. Rahal (2007) have compared their compressive strength values of RAC and NAC at different ages of concrete. For a target mean compressive strength of 50 MPa, they obtained 27.8, 41.5, 46.5 and 51.2 MPa for RAC at the ages of 7, 14, 28 and 56 days in comparison of 37.3, 46.5, 53.5 and 57.6 MPa with NAC. In the present research work the compressive strength of RAC was found to be 19.91, 24.91, 33.78 and 36.55 MPa for 7, 14, 28 and 56 days age which is 30% lower than the results of Rahal (2007).

3.2 Tensile strength of RAC

The variation of tensile strength of concrete with respect to age of concrete due to the replacement of NA with different percentages of RA is shown in Fig. 3.

From the results it was understood that the tensile strength was 2.72 MPa, 3.43 MPa, 4.89 MPa and 5.12 MPa at the ages of 7, 14, 28 and 56 days for NAC. Tensile strength of RAC reduced at all the ages of concrete, when percentage of replacement increases. The percentage of reduction in tensile strength of concrete was observed as 5%, 15% and 26% for 25, 50 and 100% replacements at the age of 7 days. At the age of 28 days the rate of reduction in strength values was 15.5%, 24%, and 34.5% for 25, 50 and 100% replacements. At the age of 56 days, it was observed to be 6%, 20% and 23% and is similar to the results of compressive strength (Fig. 4).

At the later age strength of RAC goes nearer to NAC and was an encouraging trend. It may be mainly due to the quality and source of recycled aggregate and the reason valid for compressive strength reduction is also applicable for tensile strength.

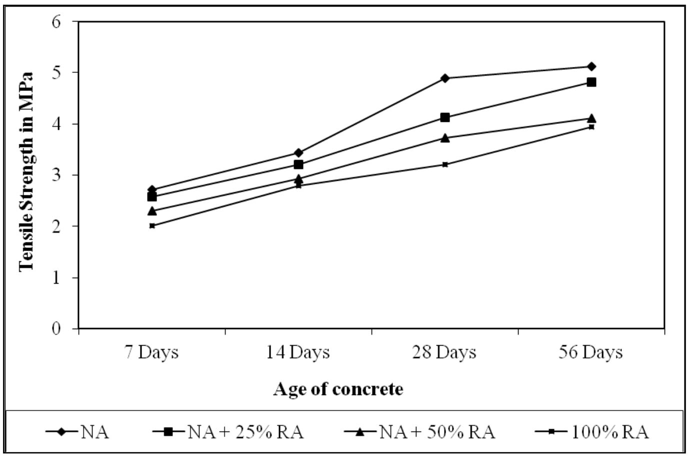

Fig. 3 Effect of RA on tensile strength

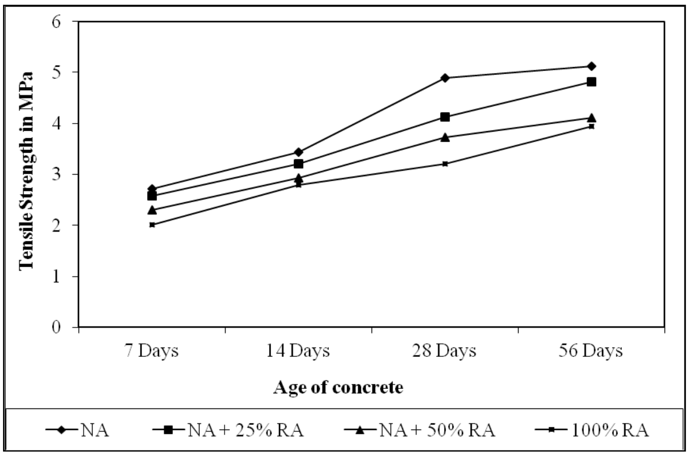

Fig. 4 Percentage reduction in tensile strength

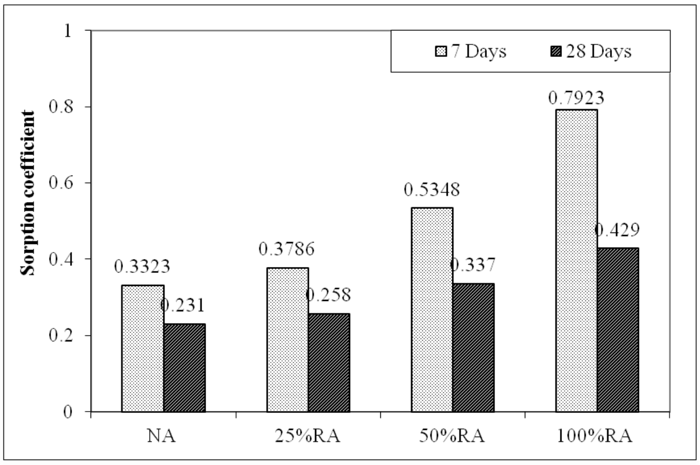

Fig. 5 Effect of RA on sorption coefficient

Table 3 Rapid chloride permeability test results

S. No	NA – RA replacement	Total charge passed in Coulombs		ASTM C1202 Standard	
				Charge Passed	Chloride permeability
		7 Days	28 Days	>4000	High
1	100 – 0%	3796(Moderate)	3285(Moderate)	2000-4000	Moderate
2	75 – 25%	3879(Moderate)	3393(Moderate)	1000-2000	Low
3	50 - 50%	4356(High)	3402(Moderate)	100-1000	Very low
4	0 – 100%	4591(High)	3627(Moderate)	<100	Negligible

3.3 Sorptivity of RAC

Generally RA has higher degree of porosity than NA. Hence the sorptivity value will be higher for RAC than NAC. In the earlier age, the sorption coefficient for natural aggregate concrete was found to be 0.33. These values were 0.38, 0.53 and 0.79 for 25, 50 and 100% replacement of NA with RA (Fig. 5).

The rate of capillary suction increases with increase in percentage of RA as substitute. The values were 13.93%, 60.94% and 138.43% increment in sorptivity value for 25%, 50% and 100% replaced RAC. Olorunsogo and Padayachee (2002) found that the surface sorptivity for the concrete mix was increased when the percentage of RA increases from 0% to 100%. They found that at the later age, sorptivity value gets decreased. They also found that the rate of reduction of sorptivity for 100% RAC with NAC was 38.5% at the age of 28 days from 47.3% at the age of 3 days. In the present work it was understood that the rate of capillary suction gets reduced with increase in age. In RAC higher capillary suction occurs due to adhered mortar in the RA. However, the overall capillary suction of a concrete would also depend on the size, distribution, interconnectivity, shape, and tortuosity of pores etc.

3.4 Chloride ion penetration resistance of RAC

The experimental results of rapid chloride penetration test conducted on NAC and RAC are given in Table 3.

From the table, it was understood that the total charge passed (in Coulombs) through RAC cylinder was greater than NAC. Therefore the chloride ion penetration was increased with the increase in percentage replacement of NA, which was similar to the results reported by Abou-Zeid *et al*. (2005). From the experimental results it was understood that 25% replacement of NA with RA gives moderate chloride ion penetration at the ages of 7 and 28 days, whereas further replacement (50 and 100% RA) increases the chloride ion penetration beyond permissible limit at the initial age (7 days) and was at moderate limit in the later age (28 days). The results were similar to the results of Olorunsogo and Padayachee (2002) and Kou *et al*. (2007). Hence from the present research work, it was concluded that the durability characteristics of RAC is comparable with NAC at a later age.

3.5 Resistance of RAC against chemical attack

The compressive strength results of specimens cured in 10% HCl solution and 10% H_2SO_4

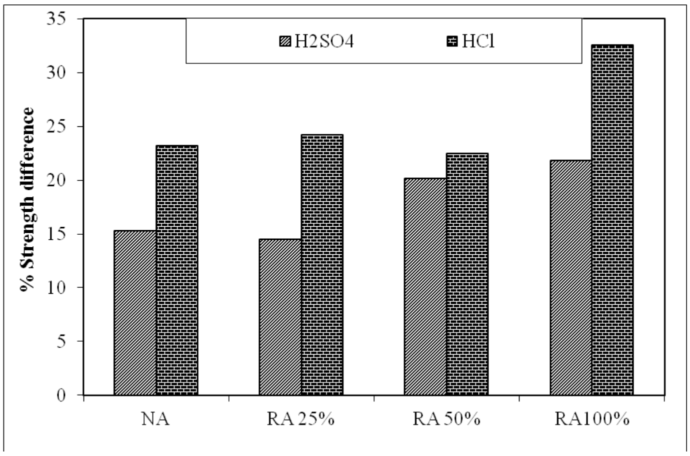

Fig. 6 Strength difference with water cured specimen

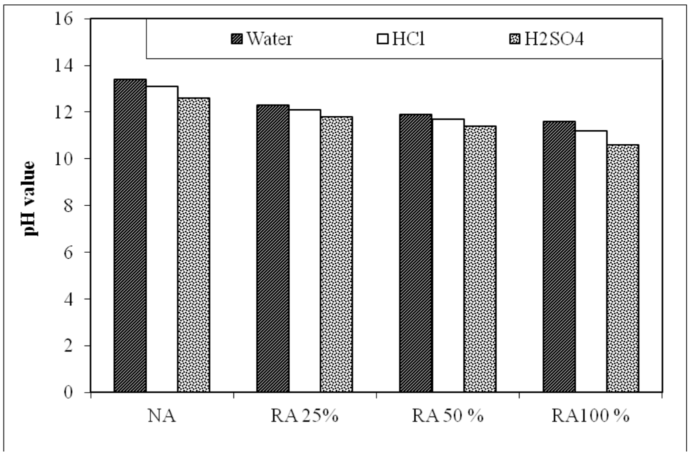

Fig. 7 Alkalinity of concrete specimens

solution were compared with specimens cured in normal water. In the case specimens cured in HCl solution, the value of compressive strength was 41.24 MPa which was 23% less than the value of concrete in normal curing for NAC. The rate of reduction for RAC was 24%, 26%, and 32% for 25, 50 and 100% NA replacements respectively. To assess the resistance against sulphate attack, the specimens were cured in 10% H_2SO_4 solution. Compressive strengths of concrete with 25, 50 and 100% NA replacement with RA were 15.49%, 20.14% and 21.78% less compared to specimens cured in normal water. For NAC this value was 15.30% less (Fig. 6).

Specimens cured in HCl solution shows higher rate of reduction than the specimens cured in H_2SO_4 solution.

The pH value is also one of the important factors to influence the corrosion in concrete. The normal pH value for the concrete to passivate the reinforcement against corrosion is 12. If the value comes below 9 the carbonation of concrete takes place and the corrosion gets initiated. From the test results it was clear that the effect of H_2SO_4 is very much higher than HCl in term of pH (Fig. 7).

The replacements of the natural aggregates with recycled aggregates decrease the resistance against corrosion in all kind of solutions. The possibility of corrosion is very high for 100% RAC when it is subjected to H_2SO_4 solution.

4. Conclusions

Detailed experimental investigations were carried out to study the effect of recycled aggregate on strength and durability characteristics of concrete and following conclusions were arrived:

Aging of the specimens increased their compressive and tensile strengths irrespective of the replacement of percentage of natural aggregate with recycled aggregate.

Compressive and tensile strength was largely affected till the age of 28 days and after that only lesser reduction in strength values were observed for RAC.

When natural aggregate replaced with 50% recycled aggregate, the compressive strength obtained was around 35 MPa, which is acceptable for structural concrete and it can very well reduce the cost of construction and will minimize the environmental problems.

From the experiments conducted it is concluded that, Concrete with 50% recycled aggregate gives reasonable compressive strength. Concrete designed for a characteristic compressive strength of 50 MPa after replacing 50% of NA with RA gives a compressive strength of 35 MPa and it can be tried in the field.

The capillary suction was directly proportional to NA replacement with RA. At the later age of concrete, NAC and RAC make only less difference in terms of capillary suction and hence the quality of RAC was found to be good.

Moderate range of chloride penetration was observed for all percentages of replacement of NA with RA. Hence it is suggested that RAC can be used for mild and moderate exposure, where chloride penetration is not a criterion.

RAC exhibits lesser resistance against chemical attack irrespective of its percentage.

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