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Research Paper

STUDY ON THE DURABILITY CHARACTERISTICS OF REACTIVE POWDER CONCRETE

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Reactive Powder Concrete (RPC), which can be classified under Ultra High Performance Concrete (UHPCs) vows to be a promising material with respect to its mechanical properties. Its performance under adverse environmental conditions is equally important, especially in marine environment, nuclear waste storage units and chemical industries. Its dense and uniform microstructure may lead to high performance characteristics. Assessing the permeability of a concrete with dense microstructure becomes important with focus on its performance. In view of this, RPC with a compressive strength of 180 MPa was produced using local available materials. Laboratory investigations like; Rapid Chloride Penetration Test (RCPT), accelerated corrosion test and acid tests were conducted to evaluate durability characteristics of RPC. The study reveals that, corrosion rate, chloride ion penetration and loss in mass and strength due to acidic environment is lower than that of high performance concrete, hence, RPC can be a promising construction material to use in aggressive environment.

Keywords: Reactive powder concrete, Rapid chloride penetration test, Accelerated corrosion test, Acid test, Durability, Corrosion rate

INTRODUCTION

Experience gained with ordinary concrete has taught us that, concrete durability is mainly governed by concrete permeability (Aitcin, 2003). Durability and strengths are two essential factors which define performance of a concrete. Reactive Powder Concrete (RPC) with high strength up to 200 MPa produced (Roux *et al.,* 1996; Richard *et al.*, 1995) is obviously to be used in special industrial construction where, high strength and durability characteristics are expected. We don't have structures aging 10 to 20 years, built using RPC in adverse environmental conditions to define its performance. Hence, laboratory investigations on durability may boost the confidence of the designer. The structures constructed in marine environment, sewer carriers, nuclear waste storage units, chemical industries often face the problem of corrosion of reinforcement, deterioration of concrete, loss in strength, etc. The decrease of the water/cementitious ratio and addition of ultrafine particles contribute to improve the life

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of concrete. The improved mechanical properties are obtained by decreasing the water/cementitious ratio and often using superplasticizers and silica fume. This reduces cement paste porosity and improves concrete durability (Roux *et al.,* 1996).

The degradation of concrete sewer pipes by sulphuric acid attack is a problem of global scope, which is neutralized by reacting with the hydration products of the concrete matrix to form gypsum and ettringite. Both gypsum and ettringite possess little structural strength, yet they have larger volumes than the compounds they replace. This results in internal pressures, formation of cracks and eventually the loss of aggregates and thinning of the wall of the concrete pipes. The direct exposure of concrete specimens to 3% (pH≈0.6) and 7% (pH≈0.3) sulphuric acid solutions accelerates the degradation of concrete specimens. It is important to note that, Thiobacillus bacteria may take years to generate such concentrations of sulphuric acid. This mainly depends on the characteristics of the wastewater and hydraulic properties of the sewer pipe (Hewayde *et al*., 2007).

Sea water can be very harmful to reinforced concrete because, once chloride ions have reached reinforcing steels, it results in a rapid spalling of the cover concrete, and consequently it is easier for chloride ions to reach the second level of reinforcing steel, and so on. The only way to inhibit, or to retard as long as possible, the corrosion of the steel by chloride ions is: to specify a very dense and impervious concrete, and place and cure it correctly, and; to increase the concrete cover. The development of all these mechanisms of aggression is closely related to the facility with which aggressive ions can penetrate concrete; therefore, it is obvious that a very dense and impervious matrix, like the one found in HPC, constitutes the best protection that can be presently offered against a marine environment (Aitcin, 2003).

Concrete is susceptible to attack by sulphuric acid produced from either sewage or sulphur dioxide present in the atmosphere of industrial cities. Changes in weight and the thickness of the test specimens are used as physical indicators of the degree of deterioration. In previous studies, weight loss, reduction in compressive strength, and change in dynamic modulus of elasticity were used to evaluate the extent of concrete deterioration due to sulphuric acid attack (Emmanuel *et al.,* 1998). Therefore, assessing the permeability of a concrete with dense microstructure becomes important with focus on its performance at microstructure level.

Taking a note on the previous studies carried out on durability and owing to its high performance characteristics, reactive powder concrete (Matte *et al*., 1999; Ehab Shaheen *et al*., 2006) with compressive strength up to 180 MPa was produced, and its durability characteristics were studied in the laboratory. RPC can be answer to requirements of a durable concrete (Hewayde *et al*., 2007) due to its fine material constituents, high cement and silica fume content, curing method adopted which leads to its dense microstructure (Roux *et al.,* 1996; Richard *et al*., 1995; Matte *et al*., 1999). To study the resistance of RPC to sulfate and chlorides and hence, the dense microstructure, three different durability tests were carried out. Chloride ion penetration into specimens of different water/

binder ratio was studied by calculating the charges passed through RPC. Loss in mass and strength in RPC specimens kept in acidic environment were studied by acid test and visual observation on surface deterioration is also reported. To study the performance of RPC under sewer acidic conditions (Hewayde *et al*., 2007) the specimens were tested by immersing in 2 pH and 0.7 pH acidic solutions. Corrosion rate of steel embedded in RPC was also studied by accelerated corrosion test. Its performance was assessed with respect to durability of normal and HPC studied earlier.

MATERIALS

The RPC specimens investigated were produced with 53 Grade, Ordinary Portland Cement (OPC) that complies with IS: 12269-1987. The mix was designed with 900 kg/m^3 cement content having density of 3120 kg/m^3 and the fineness of 3390 cm^2/g. Mineral admixture Elkem 920D silica fume with bulk density of 700 kg/m^3 was added. Polycarboxylic ether based superplasticizer was used to obtain the required workability with a lower water/binder ratio up to 0.18. Initially all the constituent materials were dry mixed and later, water and superplasticizers were added and mixed in mortar mixer having a speed of around 280 rpm. After mixing for 10 min, cube/cylinder specimens were cast and compacted by means of mechanized table vibrator. After setting, specimens were demoulded and cured at 90°C steam for 48 h, later cured at normal temperature. Two RPC mixes were designed with water/binder ratios of 0.18 and 0.20. The details of design mix are presented in Table 1.

EXPERIMENTAL PROGRAM

Aim of the program is to ascertain the durability characteristics of reactive powder concrete. The aspects concerning durability were studied using the laboratory tests such as accelerated corrosion test, Rapid Chloride Penetration Test (RCPT) and acid immersion test besides strength development.

Accelerated Corrosion Test

The RPC cylinders of size 100 mm diameter and 200 mm height were cast for the test program. Steel bar of 8 mm diameter was embedded in cylinder with 50 mm clear cover at bottom and protruding by 100 mm at top. The weight of rod was taken before embedding in concrete. The concrete samples were immersed in 3% NaCl solution. The concrete specimens were immersed up to top surface in the container. Regular DC power supply of 12 V was supplied continuously throughout the corrosion period of 15 days. Positive terminal was connected to the bar with wires (anode) and negative terminal was connected to graphite rod (cathode). The

Table 1: Mix Design and Characteristics of RPC Specimens

Mix	Water/binder Ratio	Cement kg/m^3	Sand (90-600 μm) kg/m^3	Silica fume (<100 μm)kg/m^3	Quartz powder (<45μm)kg/m^3	$f'_{c28\ days}$ MPa
RPC1	0.18	900	871	180	180	180
RPC2	0.20	900	815	180	180	165

accelerated corrosion test setup in the laboratory is shown in Figure 1. After the corrosion period, the rod was taken out, surface was cleaned and weighted. The loss in weight was calculated.

The corrosion rates were obtained from the Equation 1 (ASTM G1, 2000).

$$Corrosion\ Rate = \frac{(k \times w)}{(A \times T \times D)}\ mm / year \quad ...(1)$$

where, K is a constant, K = 8.76 × 10^4 in case of expressing corrosion rate in mm/yr, T is the exposure time expressed in hours, A is the surface area in cm^2, W is the mass loss in grams and D is the density of the corroding metal.

Figure 1: Accelerated Corrosion Test Setup in Laboratory

Rapid Chloride Ion Permeability Test

Chloride induced corrosion is considered to be one of the main causes of deterioration in concrete structures. It is caused by the penetration of chloride ions into concrete, eventually reaching the steel reinforcement. Since the ability of concrete to resist chloride penetration is an essential factor in determining concrete performance, RCPT is one of the suitable methods among the available tests to measure the chloride penetration. Rapid chloride-ion permeability test (AASHTO T-277) gives a fair idea of the interconnectivity of the fine pores in concrete that are too fine to allow water flow. Chloride-ion permeability is expressed in Coulombs (Aitcin, 2003).

In this test, a RPC cylindrical specimens of size 50 mm thick and 100 mm in diameter were subjected to DC voltage of 60 V across its thickness for a 6 h period between two cells containing sodium chloride (3% NaCl) and sodium hydroxide (0.3 N NaOH) solutions. The specimens of required thickness were sliced using water cooled diamond saw cutter from cylinders of size 100 mm diameter and 200 mm length. The sliced surface was cut perfectly plane and at right angle to the length of cylinder to avoid solution leakage from cell. Figure 2 shows the schematic diagram of RCPT set up. Figure 3 shows the image of the RCPT setup in laboratory. RCPT setup consists mainly of following three functional units like specimen conditioning unit, sample holding cell and measuring unit. The micro-processor based electronic unit provides a constant 60 ± 0.1 V DC voltage across the two circular surface of the test specimen. It also measures and displays the total electrical charge (Coulombs) that passes through the specimen. Measurement of the test time and displaying the set time as well as the remaining time during test is done by this unit. The recorded value in terms of coulomb at 360th minute is the total charges passed through the specimen.

Figure 2: Schematic Diagram of RCPT Setup

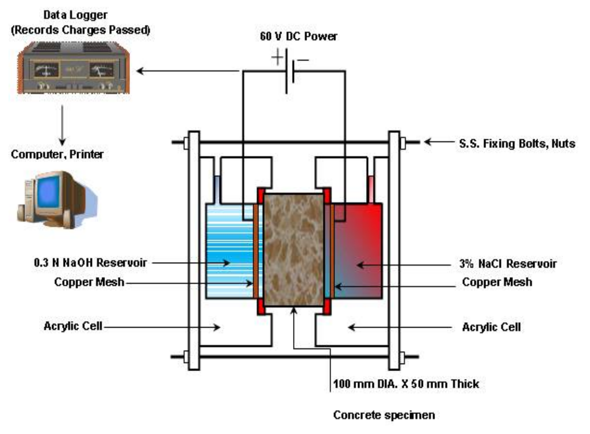

Figure 3: Specimen Preparations for RCPT

Acid Immersion Test

Acid immersion test was carried out at two different pH values; one at 2 pH and another at 0.7 to check the durability of RPC to severe and extreme conditions. Two different polyvinyl chloride containers were used for immersing the specimens in acid solutions. The two solutions of sulphuric acid were prepared by mixing concentrated sulphuric acid (H_2SO_4) with predetermined amount of distilled water. The designated pH was maintained throughout the test period in both the containers. The specimens kept in acid bath are shown in Figure 4. The RPC cube specimens of 10 × 10 × 10 cm with designated compressive strength were cast and cured for 28 days. After curing they were dried in oven and weighed, and then the specimens were kept in two containers with different pH media for 30 and 60 days exposure period. At the end of 30 and 60 days specimens were taken out from the containers, and oven dried, cooled at room temperature and weighed. To measure the surface deterioration, i.e., changes in thickness, after drying and slightly brushed on the surface, change in thickness is noted. The reduction in compressive strength and weight loss were evaluated and visual observation was reported with respect to its surface degradation.

Figure 4: Specimens Immersed in H_2SO_4 Solution

The percentage of mass loss was calculated from Equation 2 (Hewayde *et al.*, 2007)

$$\textit{Percentage Mass Loss} =$$

$$\frac{\textit{Mass before immersion}(M_1) - \textit{Mass after immersion}(M_2)}{\textit{Mass before immersion}(M_1)} \times 100 \quad ...(2)$$

The reduction in compressive strength of the tested specimens was calculated as per ASTM C267 as given by Equation (3):

$$Reduction\ in\ compressive\ strength\ \% = \frac{f'_{c28-day} - f'_{c\ after\ corrosion}}{f'_{c28-day}} \times 100 \quad ...(3)$$

where, $f'_{c28-day}$ is compressive strength at 28 days and $f'_{c\ after\ corrosion}$ is compressive strength after 30 and 60 days of immersion in sulphuric acid.

RESULTS AND DISCUSSION

Accelerated Corrosion Test Results

The corrosion rates calculated using Equation (1) are presented in Table 2. Total 6 specimens of RPC1 mix were tested to evaluate corrosion rate. The average corrosion rate of 0.096 mm/year is obtained from the test program. The study carried out earlier by Abosrra *et al.* (2011) reported the corrosion rate of 20.4 mpy (0.52 mm/year) for steel embedded in concrete with compressive strength of 46 MPa. The accelerated corrosion test period was 15 days. Similarly, Brindha *et al.* (2010) reported corrosion rate of 0.3 mm/year for the same duration in concrete with compressive strength of 35 MPa. When compared with values mentioned above, corrosion rate of steel embedded in RPC specimen is much lower. It is as low as 18.46% of that occurred in concrete with compressive strength of 46 MPa. Hence, RPC exhibits excellent corrosion resistance characteristics compared to other concretes and may be effectively utilized in marine construction. The dense microstructure due to discontinuous pore system reduces the ion exchange rate in corrosive environment. The white precipitation was observed on the top surface, which may be due the reaction of NaCl solution with concrete which has a cement content of 900 kg/m^3. No cracks were observed on the surface due to expansion by corrosion, which may be due to lower rate of corrosion rate.

RCPT Results

Two different sets of RPC specimens with water/binder ratios 0.18 and 0.20 were tested to study the effect of water binder ratio on chloride penetration. The charges passed through RPC specimens tested were

Table 2: Corrosion Rate Evaluated for RPC1 Specimens

Specimen No.	Mass of Steel Rod (g)		Mass loss (g)	Corrosion rate (mm/yr)	Average Rate (mm/yr)
	Before Corrosion	After Corrosion			
1	91.18	91.03	0.15	0.08	0.096
2	91.10	90.86	0.24	0.129	
3	91.32	91.11	0.21	0.113	
4	91.20	91.06	0.14	0.075	
5	91.18	91.01	0.17	0.091	
6	91.23	91.07	0.16	0.086	

presented in Table 3. The average charges passed through RPC1 specimens are 81 coulombs, and 109 coulombs through RPC2 specimens. From the results it may be noted that, higher charges are passed through RPC2 specimens, which have higher water/binder ratio than RPC1. Referring to ASTM C 1202:2007 for interpretation of results, the charges passed through RPC1 are found to be negligible and very low for RPC2 specimens. It represents that, RPC is more durable when corrosion resistance is considered with other class of high strength concrete. As reported by Aitcin (2003), the chloride ion permeability of the order less than 1000 C can be achieved for HPC and lower than 5000-6000 C is reported for ordinary concrete. As water/binder ratio decreases, the connectivity of the pore system decreases drastically, making the migration of aggressive ions or gas more difficult in HPC than in its plain counterpart.

The negligible penetrability of ions through RPC may due to its nature of microstructure, which was examined by both Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD), showing very dense and uniform microstructure compared to the known microstructures of conventional concrete or even HPC (Reda *et al.*, 1999). Other factors which contribute to dense homogeneity are: silica fume as a binder and filler between cement particles, elimination of coarse aggregates, crushed quartz to increase the reactivity during heat curing (Richard *et al.,* 1995). In addition, the increased density of these materials reduces the connected porosity, decreasing the penetrability to water

Table 3: Rapid Chloride Ion Penetration Test (RCPT) Record

Mix	W/B ratio	Charges Passed (Coulombs)	Average Charges Passed (Coulombs)	Chloride Ion Penetrability
RPC1	0.18	80	81	Negligible
		84		
		78		
		80		
		81		
		82		
RPC2	0.2	111	109	Very Low
		113		
		107		
		98		
		110		
		115		

and corrosive agents making these materials an attractive possibility for improved long-term durability (Surendra *et al.*, 1998).

Acid Test Results

The percentage reduction in mass and compressive strength evaluated from acid test at 30 and 60 days with two different pH media are tabulated in Table 4. The average reduction of mass in specimens kept in 2 pH media for 30 days is only 1.17% and 6.13% for 60 days. Similarly, average reduction of mass in specimens kept in 0.7 pH media for 30 days is only 12.45% and 18.51% for 60 days. The average loss in compressive strength in RPC specimens is 9.16% for specimens kept in 2 pH media for 30 days and 28.68% for 60 days. Similarly, average loss in compressive strength in RPC specimens is 41.64% for specimens

Table 4: Acid Test Results for RPC1 Specimens

Specimen No.	Initial Mass (kg)	Final Mass (kg)	pH	Test Period (days)	Mass Reduction (%)	Reduction in Compressive Strength (%)
1	2.391	2.362	2	30	01.17	09.81
2	2.423	2.392	2	30	01.15	10.93
3	2.375	2.344	2	30	00.97	09.13
4	2.390	2.354	2	30	00.99	10.70
5	2.436	2.404	2	30	01.06	05.56
6	2.434	2.389	2	30	01.68	08.81
7	2.410	2.286	2	60	05.15	28.25
8	2.420	2.320	2	60	04.13	32.05
9	2.450	2.296	2	60	06.29	26.68
10	2.420	2.280	2	60	05.79	27.36
11	2.435	2.230	2	60	08.41	27.96
12	2.428	2.266	2	60	06.67	29.75
13	2.438	2.172	0.7	30	10.91	41.76
14	2.442	2.110	0.7	30	13.52	44.15
15	2.423	2.107	0.7	30	12.93	39.00
16	2.398	1.972	0.7	60	16.93	58.56
17	2.403	1.930	0.7	60	19.68	60.15
18	2.410	1.954	0.7	60	18.92	62.04

kept in 0.7 pH media for 30 days and 60.25% for 60 days.

To compare its performance against normal and high performance concretes, few HPC and Normal Strength Concrete (NSC) samples with 60 MPa and 25 MPa compressive strengths were also tested in the same acidic solutions. The average values of loss in mass and compressive strengths are presented in Table 5. From the results it can be observed that, HPC specimens have experienced considerable loss in mass and compressive strengths after 30 days in 2 pH and 0.7 pH acidic solutions when compared with RPC. Whereas, when NSC specimens were immersed in acidic solutions for a period of 15 days only, they have undergone higher loss in compressive strength, with gain in some mass. As reported by Emmanuel *et al.* (1998), initial gain of mass in test specimens is probably due to the relative increase in volume being greater than the relative decrease in density and the test specimens initially gain weight followed by weight loss. The earlier studies carried out (Hewayde *et al.*, 2007) also have reported loss of mass up to 30% and compressive strength up to 80% when tested some HPC and NSC specimens produced with different admixtures for acid attack.

The visual observation is reported to understand the nature of surface deterioration with respect to change in color and precipitation. It can be noted that, the surface is smoothened and powder like precipitation was developed on specimens (shown in Figure 5), which were immersed in 2 pH acid solution, whereas, the surface of the specimens is peeled off from all sides which were immersed in 0.7 pH (shown in Figure 6). The surface deterioration of around 2 mm was measured from all sides on specimens kept in 2 pH and 4 - 5 mm in 0.7 pH acid solutions. The surface color changed from grey to white because of precipitation. Acid solution did not penetrate inside the specimen as no color change was found when fractured surfaces were observed after compression test, which can be seen in Figure 7. RPC is having more resistance to acid attack when compared to HPC and normal concrete. As observed by Emmanuel *et al.* (1998), the reaction between sulfuric acid and the cement constituent of concrete results in the conversion of calcium hydroxide to calcium sulfate (gypsum) which, in turn, gets converted to calcium sulfoaluminate (ettringite). Each of these reactions involves an increase in volume of the reacting solids by a factor of about two. The formation of

Table 5: Acid Test Results for HPC and Normal Strength Concrete (NSC) Specimens

Mix	Initial Mass (kg)	Final Mass (kg)	pH	Test Period (days)	Mass Reduction (%)	Reduction in Compressive Strength (%)
M60 (HPC)	2.657	2.515	2.0	30	5.344	37.44
M60 (HPC)	2.682	2.495	0.7	30	6.972	48.20
M25 (NSC)	10.956	11.293	2.0	15	- 2.98	32.16
M25 (NSC)	11.000	11.188	0.7	15	- 1.68	49.76

Figure 5: Deposition of Precipitate on Surface Due to Acid Attack

Figure 6: Surface Peels Off Due to Acid Attack

Figure 7: Fractured Surface of Specimen After Compression Test

calcium sulfate leads to softening (decrease in density) of the concrete. Both, the increase in volume and the decrease in density of the concrete due to the sulfuric acid-cement paste reaction would be larger, the higher the acidity (the lower the pH) of the acid solution.

When compared with previous studies carried out on acid resistance of normal strength and high performance concretes, RPC proves to be better with respect to resistance to acidic environment. In RPC specimens the penetration of acid solution is very less when compared to HPC and normal M25 grade concrete. This may be due to its high packing density, absence of coarse aggregates, which reduces the pores considerably. As the void space between the cement grain is being filled with finer particles of silica fume and crushed quartz.

CONCLUSION

The following conclusions may be drawn from the durability tests carried out on RPC specimens in the laboratory.

1. The average corrosion rate of steel embedded in RPC specimens evaluated is 0.096 mm/year, which indicates its better suitability to adopt in construction of structures in marine environment.
2. Chloride ion penetration through RPC specimens recorded in terms of charges passed (Coulombs) using RCPT were negligible as per ASTM C 1202:2007. The penetration increases with increase in water/binder ratio.
3. The loss of mass and compressive strength in RPC specimens, when tested in acidic

solutions are very much lower compared to HPC and NSC specimens.

4. The smoothening and increase in volume on the surface of RCP specimens was observed which may be due to reaction between the acid solution and cement constituents. No penetration of acid solution or color change across the depth was observed on the fractured surface of RPC.

From the study, it can be learnt that, RPC has better durability characteristics compared with high performance concrete. Hence, the RPC may be suitably used in the construction of sewer carriers and marine structures.

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