Journal of Asian Concrete Federation
Vol. 5, No. 1, pp. 15-24, June 2019
ISSN 2465-7964 / eISSN 2465-7972
https://doi.org/10.18702/acf.2019.06.30.15

Technical Paper

Durability and corrosion studies in prestressed concrete made with blended cement

V. V. Arora, Brijesh Singh*, and Vikas Patel

(Received October 15, 2018; Revised May 1, 2019; Accepted June 11, 2019; Published online June 30, 2019)

Abstract: Corrosion of steel embedded in reinforced concrete and prestressed concrete structures is a global problem. In general, corrosion in reinforced concrete shows some symptoms of failure before any catastrophic failure while, in prestressed concrete, sudden catastrophic failure may occur without any symptoms of failure. This could be due to the conjoint action of stress and corrosion on prestressing wires embedded in concrete. This paper presents the durability and corrosion study on two different grades M40 and M60 concretes and three different brands of cement i.e. one Ordinary Portland Cement (OPC) and two Portland Pozzolana Cement (PPC) (PPCs with fly ash content of 25 percent). The prestressed concrete beams in coastal environment were subjected to alternate wetting and drying (3% NaCl solution) and test parameters were measured for one year. Based on the durability and corrosion studies done, it can be concluded that PPC is more durable than OPC in coastal/aggressive environment owing to high resistance to chloride ion penetration in PPC. However, the carbonation test carried out on the prestressed concrete beams after six years indicated that the carbonation depth in PPC is higher than OPC. Therefore, in non-coastal region additional care with respect to concrete grade and concrete cover should be taken in design consideration.

Keywords: Prestressed concrete, corrosion, ordinary Portland cement, permeability, carbonation, Portland pozzolana cement.

1. Introduction

Recent years have witnessed numerous cases of premature deterioration of concrete structures. Simultaneously, the urgent need to inculcate durability approach in the design and construction of structures has come to the forefront. As a result, durability design provisions in standards of many countries including India have become more stringent. Among the many factors that govern the durability and corrosion resistance performance of concrete in service, type of cement receives greater attention. Corrosion is one of the major causes of deterioration in both reinforced concrete (RC) and prestressed concrete (PS) Structures.

Corrosion is generally influenced by the factors such as pH value, moisture, oxygen, carbon dioxide, chlorides, ambient temperature, relative humidity, severity of exposure, quality of construction materials, quality of concrete, cover to the reinforcement, initial curing conditions, and formation of cracks. Unfortunately, the RC structures show signs of deterioration such as spalling of cover concrete and cracking, before the stipulated service life due to various factors like climatic conditions, aggressive environments, etc., which lead to corrosion of the reinforcing bar over a period of time. However, in prestressed concrete structures, sudden catastrophic failure may occur without any such symptoms of failure. This could be due to the conjoint action of stress and corrosion on prestressing wires embedded in concrete.

Corrosion of prestressing steel is a widespread concern. Because the cross-section of each prestressing wire or strand is small and the steel is already under significant stress, small cross-sectional loss from strand or wire (compared to reinforcing bar) will cause the debonding of strand from the concrete and eventually lead to failure. In addition, it may corrode without producing outward evidence such as rust staining, cracking or spalling because the tensile stress that the small cross-section of steel generates on the cover concrete is small. Consequently, the strand or wire may debond or fail in tension without warning. If it fails in tension, it may burst from the

Corresponding author Brijesh Singh *is a Manager, National Council for Cement and Building Materials, Haryana, India.*
V. V. Arora *is a Joint Director, National Council for Cement and Building Materials, Haryana, India.*
Vikas Patel *is a Project Engineer, National Council for Cement and Building Materials, Haryana, India.*

concrete where the cover concrete cannot withstand the prestressing forces released by the failure. Once one wire (or strand) fails in tension, its load is re-distributed to others that may not have the residual capacity to sustain the extra load, so the risk to the element increases very quickly. Based on the past studies it is seen that the results of tension tests on the corroded strands recovered from the prisms after the accelerated corrosion tests demonstrated a decrease in both the strand tensile strength and ductility, which should cause great concern for the safety, serviceability and durability of prestressed concrete structures [1].

Studies showed [1] that mineral admixtures such as fly ash enhance the durability of concrete. Research concerning the use of mineral admixtures to augment the properties of concrete has been going on for many years. Unlike plain cement, fly ash mixes require longer period of time to develop strength [2]. However, fly ash leads to workability enhancement due to its spherical particles that easily role over one another reducing inter particle friction (called ball bearing effect) [3]. The critical properties affecting prestressed concrete structures such as strength, modulus of elasticity, drying shrinkage, creep, and fatigue as studied in past by National Council for Cement and Building Materials (commonly known as NCB in India) in case of Portland Pozzolana Cement (PPC) are comparable with Ordinary Portland Cement (OPC) [4]. Wear resistance of concrete is influenced by number of factors such as compressive strength, surface finish, aggregate properties, types of hardeners, and curing. The study carried out by NCB has indicated that wear resistance of concrete is primarily dependent on the compressive strength of concrete and cement type is not the governing factor [4]. In concretes containing fly ash, during the pozzolanic reaction, the fly ash reacts with the weak and porous Calcium Hydroxide (CH) to form additional C-S-H, lowering the permeability [5]. It was reported that fly ash concrete has decreased compressive strength at earlier age but increased strength at later ages, increased brittleness index, and better resistance to chloride ions penetration compared to OPC concrete [6]. Fly ash concrete indicated considerably lower drying shrinkage than OPC concrete, depending on specific surface area with fly ash and replacement ratio [6]. The resistance of concrete may differ greatly depending on the local conditions and the environmental influences. The corrosion of steel is an electrochemical process which generates a flow of current and can dissolve metals. The lower the electrical resistance, the more readily the corrosion current flows through the concrete and the greater the probability of corrosion. The metal loss as a function of time, i.e. the rate of corrosion, also increases. Thus higher the value of resistivity of a concrete specimen of given dimensions, the higher is the resistance to corrosion. The studies carried out to evaluate the performance of OPC and PPC in prestressed concrete construction include:

- Durability studies like water permeability, chloride ion permeability, chloride diffusion, carbonation depth and resistivity.
- Corrosion studies like open circuit potential measurements, cable resistance measurements and electrochemical impedance spectroscopy.

2. Experimental Data

2.1 Materials

2.1.1 Aggregates

Crushed aggregate with a nominal size of 20 mm was used as coarse aggregate and natural riv-erbed sand confirming to Zone III as per Indian Standard IS: 383-2016 was used as fine aggregate. As per Indian Standard IS: 383-2016 the zone-III fine aggregate is the sand where the percentage passing range through 4.75 mm sieve is 90-100, 2.36 mm sieve is 85-100, 1.18 mm sieve is 75-100, 600 µm sieve is 60-79, 300 µm sieve is 12-40 and 150 µm sieve is 0-10. The petrographic studies conducted on coarse aggregate indicated that the aggregate sample is medium grained with a crystalline texture and partially weathered granite. The major mineral constituents were quartz, biotite, plagioclase-feldspar and orthoclase-feldspar. The petrographic studies of fine aggregate indicated that the minerals present in order of abundance are quartz, orthoclase-feldspar, hornblende, biotite, muscovite, microcline-feldspar, garnet, plagioclase-feldspar, tourmaline, calcite and iron oxide. For both the coarse aggregate and fine aggregate sample the strained quartz percentage and their Undulatory Extinction Angle (UEA) are within permissible limits. Feldspar grains are partially fractured and shattered. The quality of both coarse and fine aggregate is fair. The properties of aggregates are listed in Table 1.

2.1.2 Cementitious material

One brand of Ordinary Portland cement and two brands of Portland Pozzolana cement with fly ash content of 25 % were used in this study. Its chemical and physical compositions are given in Table 2.

2.1.3 Superplasticizer

Polycarboxylic group based superplasticizer for M60 and Naphthalene based superplasticizer for M40 complying with requirements of IS: 9103–1979 were used throughout the investigation.

Table 1 – Properties of aggregates

Property		Fine aggregate	Coarse aggregate	
			20 mm	10 mm
Specific gravity		2.62	2.77	2.77
Water absorption (%)		0.90	0.40	0.40
Cumulative percentage passing (%)	20 mm	100	99.2	99.7
	10 mm	100	1.42	90
	4.75 mm	100	0	2.80
	2.36 mm	100	0	0
	1.18 mm	93.80	0	0
	600 µm	67.50	0	0
	300 µm	18.50	0	0
	150 µm	1.60	0	0
	Pan	0.00	0	0

Table 2 – Physical, chemical and strength characteristics of cement

Characteristics		OPC	PPC-I	PPC-II
Physical tests				
Fineness: Blaines (m^2/kg)		309	395	386
Soundness: Autoclave, Le Chatelier (%)		0.095, 2.00	0.084, 2.00	0.092, 2.00
Initial setting time: min., max. (minute)		210, 290	155, 220	150, 210
Specific gravity		3.15	2.86	2.88
Chemical tests				
Loss on ignition (LOI) (%)		2.72	3.18	2.26
Silica (SiO_2), iron oxide (Fe_2O_3) (%)		20.35, 3.48	31.63, 4.04	33.63, 3.34
Aluminium oxide (Al_2O_3), calcium oxide (CaO) (%)		4.58, 60.31	10.54, 43.22	10.39, 44.19
Magnesium oxide (MgO), sulphate (SO_3) (%)		5.25, 1.92	3.26, 1.82	2.46, 2.15
Alkalies (%)	Na_2O, K_2O	0.36, 0.58	0.28, 0.60	0.22, 0.70
Chloride (Cl), IR (%)		0.028, 2.19	0.019, 27.56	0.003, 26.12
Compressive strength				
3 days (N/mm^2)		35.82	29.80	31.20
7days (N/mm^2)		43.12	41.20	42.50
28 days (N/mm^2)		53.00	52.00	48.33

Table 3 – Concrete mix details for durability study

No.	W/C	Mix constituents				Fine aggregate (% of total aggregate by weight)	28-day strength of concrete (N/mm^2)
		Cement type	Cement (kg/m^3)	Water (kg/m^3)	Admixture by weight of cement (%)		
M40A20 Grade, workability = 50-75 mm with chemical admixture, moderate exposure condition							
1	0.38	OPC	400	152	1.00	40.00	48.33
2	0.37	PPC-I	411	152	1.00	39.50	48.60
3	0.35	PPC-II	434	152	1.00	39.00	48.74
M60A20 Grade, workability = 50-75 mm with chemical admixture, moderate exposure condition							
4	0.30	OPC	443	133	0.80	39.00	68.94
5	0.28	PPC-I	475	133	0.80	38.50	69.25
6	0.27	PPC-II	493	133	0.80	38.00	68.31

Table 4 – Concrete mix design details for corrosion study

No.	W/C	Mix Constituents				Fine aggregate (% of total aggregate by weight)	28-day strength of concrete (N/mm^2)
		Cement type	Cement (kg/m^3)	Water (kg/m^3)	Admixture by weight of cement (%)		
M40A20 Grade, workability= 50-75 mm with chemical admixture, severe exposure condition							
1	0.400	OPC	400	160	0.70	34.50	49.18
2	0.347	PPC-I	460	160	1.10	32.50	49.37
3	0.340	PPC-II	456	155	0.90	33.00	48.65
M60A20 Grade, workability: 50-75mm with chemical admixture, severe exposure condition							
4	0.300	OPC	433	130	1.10	35.5	68.59
5	0.280	PPC-I	464	130	1.10	34.5	69.14
6	0.260	PPC-II	500	130	1.00	34.5	69.12

2.2 Mix design and sample preparation details

Two different grades of concretes, i.e. M40 and M60 with two different types of cement, i.e. OPC and PPCs, were used in this study. For each grade, three separate batches were prepared: one with OPC and two with PPCs for carrying out durability studies at NCB, Ballabgarh. Further, for each grade, three more separate batches were prepared: one with OPC and two with PPC for carrying out corrosion studies at Central Electro Chemical Research Institute (CECRI), Karaikudi, India. The slump of the fresh concrete was kept in the range of 50-75 mm. A pre-study was carried out to determine the optimum superplasticizer dosage for achieving the desired workability based on the slump cone test as per Indian Standard IS: 10262-2019. The mix design details of specimens are given in Tables 3 and 4.

The concrete mixes were prepared in pan type concrete mixer. After 24 hours, the specimens were striped from their respective molds. The laboratory conditions of temperature and relative humidity were monitored during the curing, i.e. 27 ± 2°C and relative humidity 65 ± 5%. For carbonation study, the prestressed concrete beams were cast at NCB, Ballabhgarh and cured for 28 days using hessian cloth. The concrete cover provided for prestressed concrete beams were 30 mm. The overall length of the beams was 2.3 m. Each beam consisted of a rectangular uniform cross section of 200 x 250 mm and was longitudinally prestressed using six strands placed across beam cross section (four prestressed strands at the bottom and two at the top). The strands had diameter of 12.7 mm with ultimate tensile strength of 1,570 MPa. The Gifford-Udall (CCL) system of post-tensioning was used for anchoring prestressed force.

2.3 Experimental program

2.3.1 Durability studies

Different sizes and types of specimens as per relevant Indian codes/International codes/test methods/specifications were used to perform the tests. The rapid chloride ion permeability test was carried out at 28 days on cylindrical specimens as per ASTM C-1202 as this study was mainly pertaining to comparison of OPC and PPC concretes. The water permeability test was carried out at the age of 28 days on concrete cylinder as per DIN-1048. Resistivity test was carried out using four probe Weiner resistivity meter and manufacturer's literature and BS 1881 part 201 was used as a guide. In order to determine the depth of carbonation, the prestressed concrete beams exposed to outdoor environment (directly exposed to sunlight and rain) at NCB, Ballabgarh were used. Readings for carbonation depth were measured using phenolphthalein solution and CO_2 concentration in atmosphere were recorded using handheld CO_2 meter. Accelerated carbonation test was carried out as per ISO: 1920 part 12 on concrete cube specimen with dimension 150x150x150 mm. After 28 days of water curing, the concrete specimens were moved to and stored in laboratory environment (temperature = 27±2°C and relative humidity = 65±5%) for 62 days. After 62 days of laboratory conditioning, top and bottom longitudinal faces and two end faces of the beam were sealed using paraffin wax and carbonation was allowed on two faces. After the sealing, the concrete beam specimens were shifted to the carbonation chamber where CO_2 = 4 ± 0.5 %, temperature = 27 ± 2°C and relative humidity = 65 ± 5%. The carbonation depth was measured by approximately cutting a 50-mm-thick slice from the concrete cube specimen and exposing the cut surface to 1% phenolphthalein solution. The concrete beam specimens were exposed to carbon dioxide for 70 days.

2.3.2 Corrosion studies

For corrosion studies, the prestressed concrete beams were cured in steam curing chamber for two hours for the process of initial setting of concrete. Then, the prestressed beams with bed was kept in the steam curing chamber one over the other and a thick tarpaulin sheet was completely covered the steam curing chamber in order to prevent even a minor leakage of steam at any place of chamber and also to maintain the prefixed temperature. Later, the temperature of the chamber was gradually raised from room temperature to 75℃. This took around 2 ½ hours and this period is known as raising period. Then this 75℃ was constantly maintained for a period of four hours and this is known as constant period. After that, the temperature inside the cooling chamber was gradually reduced from 75℃ to room temperature. The time taken for this operation was about 2 ½ hours and this is known as cooling period.

For evaluating corrosion performance, six prestressed concrete beams for each cement type (OPC, PPC-I and PPC-II) were cast for both M40 and M60 grade concretes and three tests namely open circuit potential measurements, cable resistance measurements, and electrochemical impedance spectroscopy studies were conducted for one-year period. These prestressed concrete beams were cast as per Hoyer's Long Line system of petitioning in a factory. The probability of prestressed steel to corrode in coastal environment was assessed by measuring the open circuit potential of embedded steel with respect to a saturated calomel electrode in normal condition (distilled water, DW) and severe condition (3% NaCl Solution with Alternate Wetting and Dry, AWD). The PS wire embedded in the PS concrete beams was connected to the positive terminal of the voltmeter and the reference electrode was connected to the negative terminal of the high impedance voltmeter. The reference electrode along with its outer container, having a porous plug at the bottom filled with 0.4N NaOH solution was kept on the concrete surface just above the PS steel wire and the stable reading was noted. Open circuit potential (OCP) being a thermodynamic quantity will not indicate the extent and rate of corrosion. In the vicinity of a corrosion site in a beams, the value of corrosion potential measurements made between a single half-cell and the PS steel may indicate probabilities of corrosion risk in prestressed concrete beams. A volt meter with accuracy of ± 10 mV was used. Saturated Calomel Electrode (SCE) was used as reference electrode. The system is represented as Hg / $HgCl_2$/ Saturated KCl. It has a stable potential of + 242 mV vs. hydrogen electrode. The probability of prestressed steel to corrode was assessed by measuring the open circuit potential of embedded steel with respect to a saturated calomel electrode in normal condition (distilled water) and severe condition (3% NaCl Solution). The technique which was made use of in measuring the cable resistance of the prestressing wires is known as four probe technique (See Fig. 1) where the contact resistance is eliminated and the resistance of the connecting wires is not included in the measurements.

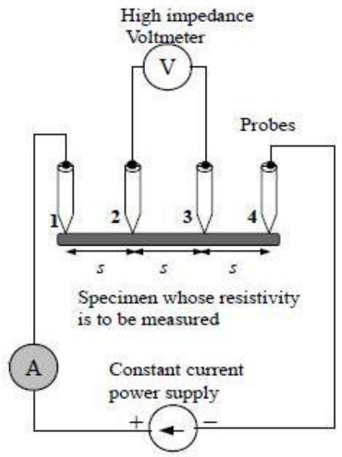

Fig. 1 – Four probe method for measuring resistivity of specimen [9]

Fig. 2 – EIS measurement on PS beam is in progress

The prestressed concrete beams used for open circuit potential and cable resistance measurements were used for Electrochemical Impedance Spectroscopy (EIS) measurement (See Fig. 2). This measurement was carried out on a three electrode corrosion cell, using portable PARSAT 2263 Advanced Electrochemical system, UK. A stainless steel plate measuring 150 mm x 50 mm and a Saturated Calomel Electrode (SCE) were used as a counter and reference electrodes, respectively. The EIS spectrum was collected over the frequency range of 0.01 to 10,000 Hz using a potential perturbation of 20 mV at the rest potential. Later on Charge transfer resistance (Rct) of prestressing wire was directly obtained from the Z view software.

A few concrete core samples were extracted from prestressed beams exposed to severe environment like alternate wetting and drying in 3% NaCl solution for one year and chloride percentage in hardened concrete was determined by Acid Soluble Chloride method and Water Soluble Chloride Method. The chloride percentage was determined by profile grinding concrete core samples at every two- to three-mm depth up to 10 mm for comparing chloride ingress in OPC and PPC concretes. After 10-mm depth the acid soluble and water soluble chloride by weight of concrete was not varying much for both OPC and PPC concretes. The chloride diffusion coefficients were worked out using regression analysis. The chloride diffusion coefficients were determined by profile grinding concrete core samples at different depths. The detail of test carried out is given in Table 5.

Table 5 – Details of tests carried out

No.	Type of test	Standard/code	Type of specimen	Specimen Size (mm)
1	Rapid chloride ion permeability	ASTM C-1202	Cylinder	Dia.= 100, Ht.=200
2	Water permeability	DIN-1048	Cylinder	Dia.=150, Ht.=150
3	Accelerated carbonation test	ISO: 1920 part 12	Cube	150x150x150
4	Resistivity test	BS 1881 Part 201	Cylinder Prism Slab	Dia.= 100, Ht.=200 150x150x700 600x600x100
5	Open circuit potential measurement	ASTM C-876	Prestressed Concrete Beam	200 x 250x2300
6	Electrochemical impedance spectroscopy (EIS)	ISO:16773 (1)		
7	Cable resistance measurement	ASTM B-193		
8	Chloride diffusion coefficient	ISO:1920 Part-11	Concrete core extracted from Prestressed Concrete Beam	Dia.=60

Table 6 **–** Test results of rapid chloride ion and water permeability test

No.	Concrete grade	Cement type	Charge Passed (Coulombs)		Depth of water penetration at 28 days (mm)
			28 days	56 days	
1	M-40	OPC	2487	1741	9.33
2		PPC-I	648	570	6.56
3		PPC-II	585	515	6.33
4	M-60	OPC	1020	812	5.33
5		PPC-I	269	249	4.00
6		PPC-II	211	196	4.67

3. Results and Discussions

3.1 Durability studies

3.1.1 Rapid chloride ion permeability test (RCPT), water permeability test and resistivity test

The rapid chloride ion permeability test was carried out at the age of 28 and 56 days on a cylindrical specimen of size 100-mm diameter and 200-mm height as per ASTM C-1202. This test measures the ability of concrete to resist the penetration of chloride ions and the results are measured in coulombs. The test results of rapid chloride ion permeability test for M40 and M60 grade concretes using OPC and PPCs are given in Table 6. The results of rapid chloride ion permeability test show that fly ash would significantly limits the ingress of chloride ions into the concrete. This is mainly due to the increased amount of Calcium Silicate Hydrate (C-S-H) phase which is the “glue” that is responsible for the concrete’s strength and impermeability [7]. The results of rapid chloride ion permeability test (See Table 6) and water permeability test (See Table 6) show that the PPC would significantly limit the ingress of chloride ions and water into the concrete, thus increasing durability if used in coastal environment [7,8].

Resistivity of concrete was measured using a resistivity meter on three types of concrete specimens: concrete cylinder of 150-mm diameter and 300-mm height, concrete prism with cross section of 150 mm x 150 mm and length of 700 mm, and concrete slabs with cross section of 600 mm x 600 mm and thickness of 100 mm. Wet curing of the specimens was done for three different time periods. The specimens were then taken out of the curing tank and testing was done while the surface of the specimen was still wet. The surface of the specimen to be tested was first made moist with water. For measuring the value of resistivity of concrete, BS 1881 part 201 was used. The resistivity probe was then placed on the surface of the specimen at several locations and the average of the readings was taken. The average value of resistivity is shown in Table 7. From the results, it can be seen that the value of resistivity for M40 and M60 grade concretes in case of PPC is higher than OPC, irrespective of the period of curing (for period of 14, 28, 540 days). Therefore, indicating that PPC made concrete has higher resistance to corrosion than OPC made concrete for both M40 and M60 grade concretes.

Table 7 – Resistivity of concrete for M40 grade concrete

No.	Cement type	Specimen type	Age at testing (days)	Resistivity (kΩcm)	
				M40	M60
1	OPC	Concrete cylinder	28	13.33	17.45
2	PPC-II		28	19.33	24.87
3	OPC	Concrete prism	14	11.67	18.87
4	PPC-I		14	20.00	29.00
5	OPC	Concrete slab	540	53.00	69.00
6	PPC-I		540	99.00	99.00

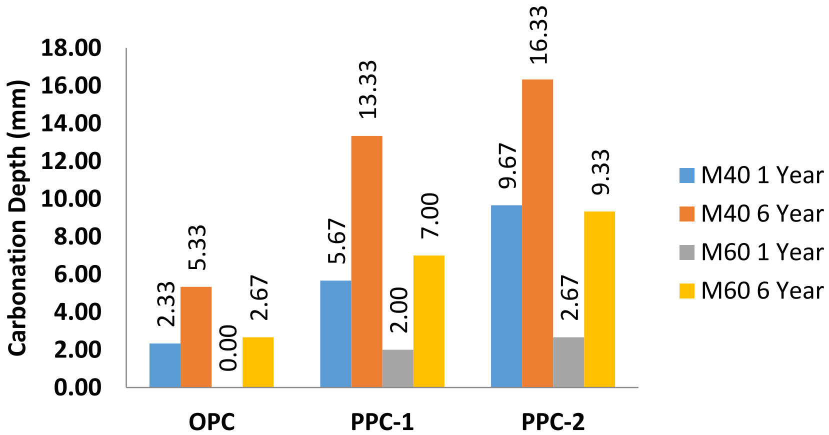

Fig. 3 – Variation in carbonation depth

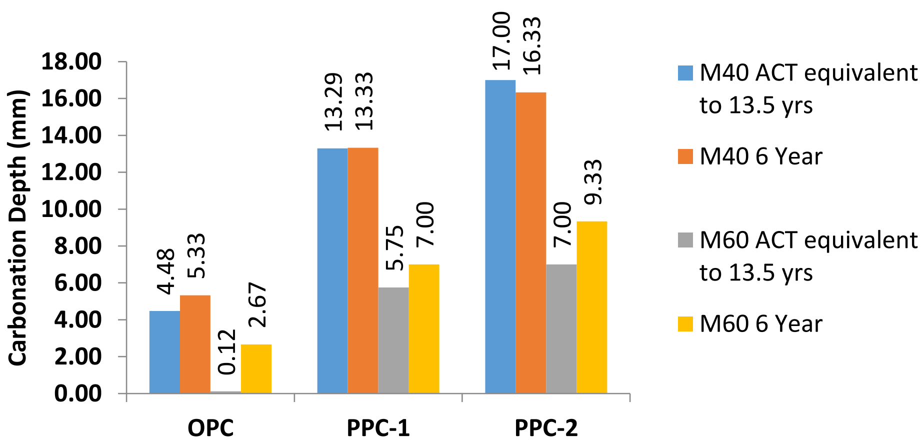

Fig. 4 – Carbonation depth comparison in field test and accelerated carbonation test in laboratory

3.1.2 Carbonation test

In order to determine the depth of carbonation, carbonation test has been carried out on prestressed concrete beams exposed to ambient conditions. 60-mm diameter core samples have been taken on these PS beams using concrete core drilling machine. The locations of the core have been carefully marked at the centre of the top surface of the PS beams, so that there will not be any disturbance on the stressed PS wires located at the top of the beams. These core samples have been taken at the age of 1 year and 6 years, respectively. Phenolphthalein solution was sprayed on the core sample. The colour change was measured at five places from top surface of the core sample and the average depth of carbonation was taken. Figure 3 shows the depth of carbonation measured on core samples collected on the respective PS concrete beams made with M40 and M60 concretes, respectively. The average CO_2 level near these prestressed concrete beams was recorded as 368 PPM using handheld CO_2 metre. The average humidity range for the region in which these beams were tested was between 50-55 % as per Indian Meteorological Department.

A significant carbonation depth was measured after the six years of exposure in non-coastal environments. The carbonation test results show that the OPC performs well in resisting the ingress of carbon dioxide with less carbonation depth as compared to that of the concrete made with PPC. The carbonation depth in case of M60 grade concrete is lower as compared to M40 grade. The comparisons are also made between the field test done on prestressed concrete beams for M40 and M60 grade concretes and accelerated carbonation test as per ISO:1920 (Part-12) done of concrete cube samples of M40 and M60 grade concretes. The results are shown in Fig. 4.

The carbonation depth measured at the age of 6 years in prestressed concrete beams are higher as compared to accelerated carbonation test done in laboratory at exposure period of 72 days which is equivalent to field exposure of structure to about 13.5 years considering CO_2 concentration of 500 ppm. The higher carbonation depth obtained in case of prestressed concrete beams exposed to natural carbon dioxide as compared to accelerated carbonation test can be attributed to the depths of carbonation predicted from the accelerated conditions are with respect to controlled conditions of temperature and humidity. But in case of prestressed concrete beams, six years exposure was with respect to varying level of carbon dioxide over the six year period in the atmosphere. In addition to this, the prestressed concrete beams were also subjected to the weather with varying temperature and humidity including sunshine, wind, wetting and dry cycles due to rain. These microclimatic factors such as temperature and humidity, sunshine, wind, wetting and drying cycles (due to exposure to rain) might have been responsible for the increased carbonation depth in concrete under natural environment. Hence, a higher grade concrete or additional cover act in countering impact of carbonation induced corrosion in case of concrete with PPC. Better performance in terms of carbonation resistance was observed in M60 grade concrete as compared to M40 grade concrete for both OPC and PPC made concrete where in both PPC, the fly ash content was 25 percent.

3.2 Corrosion studies

3.2.1 Open circuit potential measurement

For reinforcement rod embedded in concrete, the corrosion condition in terms of probability of corrosion based on the open circuit potential measurement can be classified with the help of ASTM C876. But no such standards are available to classify the probability of corrosion based on the potential measurements for PS wires embedded in concrete. Hence a basic study has been carried out on PS steel wires embedded in simulated concrete environment, so as to generate data for interpretation of our results. The results are shown in Fig. 5.

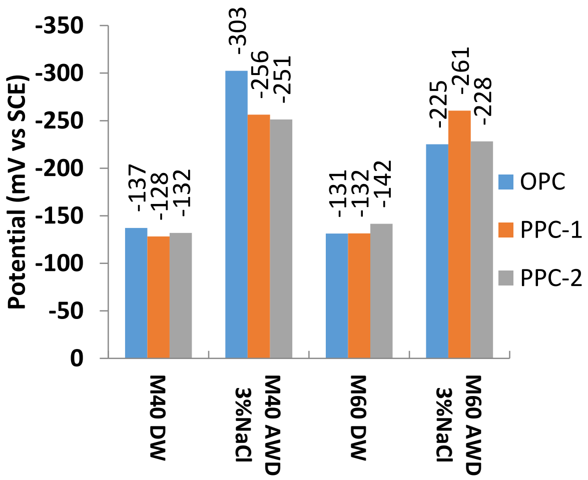

Fig. 5 – Variation in potentials

From this study, it is clear that the potential time behaviour of top and bottom PS wires embedded in PPC and OPC concretes exposed to the normal condition indicate the passive nature of rebar even after one year of exposure, whereas both top and bottom PS wires embedded in PPC and OPC concretes exposed to 3% NaCl condition exhibit active passive behaviour. The results of basic studies carried out on PS wires immersed in cement extract with and without chloride reveal that if the potential value crosses

-550 mV then only severe corrosion products will be formed on the surface of the prestressing wire. Based on simulated concrete environmental results, it can be concluded that the prestressing wires embedded in both OPC and PPC concretes are in active passive condition only.

3.2.2 Electrochemical impedance spectroscopy (EIS)

The EIS measurement on prestressed concrete beams was carried out on a three electrode corrosion cell, using portable PARSAT 2263 Advanced Electrochemical system, UK, and results are shown in Fig. 6. The results of electrochemical impedance spectroscopic data show that in severe environmental condition, higher Rct values obtained in PPC concretes could be due to the impermeable nature of PPC concretes when compared to OPC concrete. Electrochemical Impedance Spectroscopic (EIS) study reveals that, in general, PPC cement behaves in better manner than OPC cement even in the severe environment like alternate wetting and drying in 3% NaCl solution.

3.2.3 Cable resistance measurement

The technique used in measuring the cable resistance of the prestressing wires is known as four probe technique where the contact resistance is eliminated and the resistance of the connecting wires is not included in the measurements and results are shown in Fig. 7. The results of cable resistance measurements distinctly show that irrespective of type of cement, grade of concrete and type of exposure conditions, all the measured resistance values are far below the theoretically assessed resistance value of 9.20 mΩ. This clearly indicates the passive nature of the embedded PS wires in the respective concretes. Irrespective of the type of exposure condition, embedded PS wires exhibit similar fashion in all the three types of cements throughout the test period. Irrespective of the type of cement, both PPC and OPC cements display similar behaviour. This behaviour enlightens the uncorroded state of the embedded PS wires even in severe environment like 3% NaCl condition. The behaviour of PS wires embedded in OPC and PPC concretes was similar.

3.2.4 Chloride diffusion coefficient on prestressed concrete beams

The chloride diffusion coefficients for M40 grades concrete made with OPC, PPC-I, and PPC-II were 50 mm^2 /year, 32 mm^2 /year and 35 mm^2 /year respectively. The test results also indicate that ingress of chloride in PPC concrete is less as compared to OPC concrete and therefore it is better for coastal environments as summarized in Table 8.

The result of corrosion studies in general indicates better resistance to corrosion in case of PPC after one year of exposure in the severe environment like alternate wetting and drying in 3% NaCl solution. Corrosion initiation indicated in both OPC and PPC for M40 grade. However, no significant corrosion of PS wires has been seen after one year of exposure in OPC. The durability and corrosion studies results are in line with chloride determination by chemical analysis on hardened concrete samples.

4. Conclusion

Based on the durability and corrosion studies done, it can be concluded that PPC is more durable than OPC in coastal environment/aggressive environment owing to high resistance to chloride ion penetration in PPC. The performance indicated by RCPT test and chloride determination by chemical tests is in line with corrosion test results mainly open circuit potential measurements and electrochemical impedance spectroscopy studies.

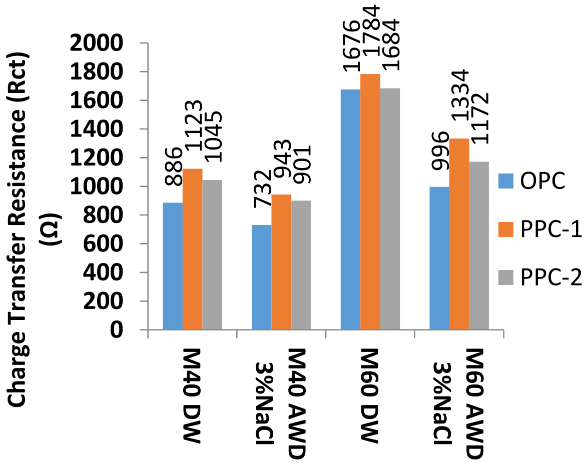

Fig. 6 – Variation in charge transfer resistance (Rct)

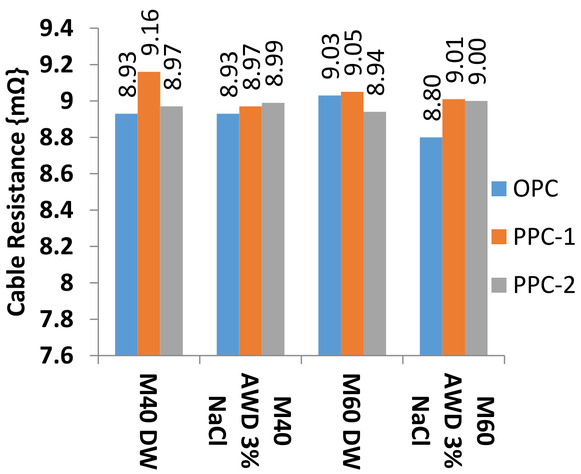

Fig. 7 – Variation in cable resistance measurement

Table 8 –Test results of chemical analysis of concrete cores extracted from prestressed concrete beams exposed to 3% NaCl solution for one year

No.	Cement type	OPC M40 (compressive strength = 45.54 N/mm^2)		PPC-I M40 (compressive strength= 45.40 N/mm^2)		PPC-II M40 (compressive strength = 48.32 N/mm^2)	
	Depth of concrete core Profile (mm)	Acid soluble chloride (%) by weight of concrete	Water soluble chloride (%) by weight of concrete	Acid soluble chloride (%) by weight of concrete	Water soluble chloride (%) by weight of concrete	Acid soluble chloride (%) by weight of concrete	Water soluble chloride (%) by weight of concrete
1	0-1	0.47	0.28	0.47	0.18	0.53	0.17
2	1-3	0.36	0.26	0.35	0.20	0.37	0.18
3	3-5	0.37	0.24	0.25	0.18	0.26	0.16
4	5-7	0.29	0.25	0.15	0.11	0.16	0.10
5	7-10	0.28	0.23	0.07	0.04	0.10	0.05
6	10-30	0.27	0.22	0.07	0.03	0.08	0.04

The test result of carbonation test indicates that carbonation depth in OPC made concrete is less as compared to PPC made concrete for both M40 and M60 Grade concrete where, in both PPCs, fly ash content was around 25 percent. The field test results of carbonation depth were higher than the accelerated carbonation test method as per ISO-1920 Part-12.

Based on the carbonation studies done in field and by accelerated test method in laboratory, it can be concluded that the OPC is more durable in non-coastal / normal environment. The points to be taken care of while using PPC in prestressed concrete will be early age strength, curing period and little extra cover to take care of carbonation.

References

1. Mirza S.M. and Ali Hussam (2015) “Corrosion in Prestressed Concrete, Book on Application of Codes, Design & Regulations”, pp.137-149
2. Langley W.S.; Carette G.; Malhotra V.M. (1989) ‘Structural concrete incorporating high volume ASTM Class F fly ash’, ACI Materials Journal, 86, pp. 507 – 514.
3. Gopalan M.K. (1993) Nucleation, “Pozzolanic factors in strength development of class F fly ash concrete”, ACI Materials Journal, 90(2), pp. 117 – 120.
4. Sengul O.; Tasdemir C.; Tasdemir M.A. (2005) “Mechanical properties and rapid chloride permeability of concretes with fly ash”, ACI Materials Journal, 102(6), pp.474-482.
5. V.V. Arora; Brijesh Singh; Amit Prakash; Arup Ghatak (2013) “Use of Portland Pozzolana Cement for RCC and Prestressed Concrete”, Thirteenth NCB International Seminar on Cement and Building Materials, New Delhi.
6. W.E. Eliss, Jr.; E.H. Riggs; W.B. Butler (1991) "Comparative Results of Utilization of Fly Ash, Silica Fume and GGBFS in Reducing the Chloride Permeability of Concrete", Proceedings of the Second CANMET/ACI International Conference on Durability of Concrete, Montreal, Canada, V.M. Malhotra, Ed., ACI Publication SP-126, 1, pp. 443-458.
7. V.V. Arora; Brijesh Singh; S.K. Mehta; Suresh Kumar (2011) “Studies On Engineering Properties Of Plain Concrete Made with Portland Pozzolana Cement And Ordinary Portland Cement”, Twelfth NCB International Seminar on Cement and Building Materials, New Delhi.
8. V.V. Arora and Puneet Kaura, (2017) “Service life prediction of RC structures using short term durability testing methods / techniques”, 15th NCB International Seminar, Delhi.
9. Xiao Zi Yuan (2009) “Electrochemical Impedance Spectroscopy in PEM Fuel Cells: Fundamentals and Applications”, Springer.