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ScienceDirect
Cement & Concrete Composites 29 (2007) 136–145
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Corrosion behaviour of blended cements in low and medium strength concretes

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Received 29 March 2006; received in revised form 31 August 2006; accepted 18 October 2006
Available online 1 December 2006

Abstract

The corrosion behaviour of steel in concrete with blended cements like Portland pozzolana cement and Portland blast furnace slag cement were studied in comparison to their corresponding ordinary Portland cements from the same production facility with the same clinker used in their production. The different cements studied were – two Portland pozzolana cements (PPCs) and their corresponding ordinary Portland cements (OPCs) from the same cement plant, and two blast furnace slag cements (BFSCs) along with the corresponding OPCs from the same factory. Three concretes of compressive strengths 15, 30 and 45 MPa were designed. The corrosion characteristics of fly ash and slag cement concretes were studied through measurement of resistivity, pH, carbonation, and corrosion rate. The resistivities of both fly ash and slag concretes were found to be more than the corresponding ordinary concretes. The pH of fly ash and slag concretes were found to be around 12.0 indicating no significant lowering compared to OPC concrete. However, carbonation was higher in both blended cement concretes, particularly in slag concretes. The corrosion rates of steel in both fly ash and slag concretes were much lower than the corresponding OPC concretes, with slag concretes showing higher resistance than fly ash concretes. From these studies it is evident that fly ash and slag blended cements performed better than their corresponding ordinary cements, with slag cements showing the best corrosion resistance.

Keywords: Blended cements; Resistivity; Alkalinity; Carbonation; Corrosion rate

1. Introduction

In recent years many researchers have established that the use of supplementary cementitious materials (SCMs) like fly ash, blast furnace slag, silica fume, activated metokaolin, rice husk ash etc., can improve the various properties in fresh and hardened states of concrete. In fresh concrete, these SCMs improve workability and reduce the heat of hydration, whereas in hardened concrete they reduce the permeability by the pozzolanic reaction thereby increasing the durability [1,2]. The performance of these SCMs depends mainly upon the level of incorporation of these materials in cement and may vary with the country or the manufacturer. In many advanced countries these are usually added during mixing at the batching plant. In India where majority of the construction is carried out by adopting labor intensive techniques the cement manufacturers supply factory produced 'Blended cements'. It was recently reported that the concrete made with intergrinding blended cement gains strength more rapidly than site blended cement [3]. Examination of the microstructure of the cements produced by intergrinding showed that the process of intergrinding breaks up agglomerates of these fine particles rather than fracturing the particles themselves.

In blended cements, the rate of development of strength at earlier ages is low when compared to ordinary Portland cement (OPC); in the long term, concretes with blended cements may gain equivalent or higher strengths [1,4].

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doi:10.1016/j.cemconcomp.2006.10.005

The development of strength in blended cement concretes depend on the replacement level of fly ash/slag, chemical and mineralogical composition, mix proportions and curing. Meusel and Ros [5] reported that in slag cement concrete, strength increase was observed up to 50% replacement of cement with slag, and thereafter the strength reduced. Berry and Malhotra [4] observed that in pozzolanic cement concrete, if the replacement level is more than 25% there is a marginal reduction in strength. Thomas et al. [6] and Marsh et al. [7] reported that a curing period of about 28–90 days might be required for concrete with mineral admixtures to attain properties similar to that of ordinary Portland cement concrete. Lane and Best [8] investigated the strength up to 1 year and reported that in fly ash concrete the strength at the end of 1 year was 20% more than ordinary Portland cement concrete. Khatri et al. [9] investigated the effect of curing on the water permeability of slag and Portland cement concrete. In their investigation, higher binder content and low w/c ratio was used in slag concrete. They also found that the co-efficient of water permeability of slag concrete was less than that of OPC concrete even after 7 days curing. Hakkinen [10] investigated the microstructure and permeability of high strength (55 MPa) slag concrete and reported that in slag concrete micro cracks were more than Portland cement concrete.

The above discussions show that most of the investigations were on concretes with fly ash and slag added as mineral admixtures, and very limited information was available on factory produced blended cements in concrete. In view of the above an attempt has been made in the present investigation to compare the performance of concretes made with factory produced blended cements. Two Portland pozzolana cements (fly ash based) and two Portland blast furnace slag cements were assessed for the strength and corrosion behaviour in comparison to their corresponding ordinary Portland cements from the same factory with the same clinker used in their production.

2. Experimental investigations

2.1. Materials

Totally eight cements were considered in the present investigation – OPC-1 to OPC-4 were all of ordinary Portland Cements (OPCs), two Portland pozzolana cements (PPC-1 and PPC-2) and two Blast furnace slag cements (BFSC-3 and BFSC-4). A comparison can be attempted specifically between PPC-1 and OPC-1, since both are obtained from the same cement plant and clinker being the same in their production and similarly PPC-2 and OPC-2 were obtained from a different cement plant. Also BFSC-3 corresponds to OPC-3 and BFSC-4 corresponds to OPC-4, each set obtained from a different cement plant. The chemical characteristics of these cements have been presented in Table 1. All ordinary Portland cements confirm to IS 8112 [11], Portland pozzolan cements (fly ash based) confirm to IS 1489-Part I [12], whereas blast furnace slag cements (slag based) confirm to IS 455 [13]. The blending of fly ash and slag in both the blended cements was at 20% and 50% by weight. Well graded river sand and good quality crushed blue granite are used as fine and coarse aggregates respectively. The different size fractions of coarse aggregate (20 mm down graded and 12.5 mm down graded) were taken in order to get a dense concrete. The sand was sieved through 4.75 mm to avoid the presence of pebbles and organic matter, and the fineness modulus was 2.80. The specific gravities of coarse aggregates and fine aggregates are 2.70 and 2.65 respectively. Potable tap water was used for mixing and curing.

2.2. Mix design, demolding and curing

The concretes were designed for the strength grades 15, 30 and 45 MPa with a slump of 25–50 mm as per the ACI 211.1. [14]. The corresponding mix proportions are presented in Table 2. All the concretes were thoroughly mixed in a laboratory planetary mixer and the slumps were measured. The specimens cast were demoulded the next day and immersed in normal water. In the case of sea water curing, the specimens were removed from the normal water and immersed in sea water after three days (this time period was chosen to ascertain a minimum strength for the concrete).

2.3. Test program

In the present investigation the strength characteristics have been assessed both through the compressive and split tensile strengths. The corrosion characteristics were studied

Table 1
Chemical composition of OPCs, PPCs and BFSCs

Characteristic	OPC-1	OPC-2	OPC-3	OPC-4	PPC-1	PPC-2	BFSC-3	BFSC-4
Silica (SiO_2) %	20.30	20.8	21.7	20.78	18.2	16.4	20.32	25.68
Ferric oxide (Fe_2O_3) %	4.5	4.5	2.8	4.70	4.2	3.5	3.60	3.64
Alumina (Al_2O_3) %	6.0	5.2	8.5	5.67	6.0	5.7	12.0	12.36
Calcium oxide (CaO) %	58.2	63.6	57.5	62.12	50.25	58.0	45.3	49.73
Magnesium oxide (MgO) %	1.0	0.9	2.9	1.47	0.9	0.9	6.4	4.42
Sulphuric anhydride (SO_3) %	1.6	2.0	2.6	2.68	1.9	2.0	2.2	2.38
Loss on ignition (LOI) %	2.30	2.1	1.2	1.33	2.4	2.0	1.4	1.85
Insoluble residue (IR) %	1.0	0.9	1.8	1.21	8.9	11.3	2.0	1.78
Pozzolanic material used	0	0	0	0	20	20	50	50

Table 2
Details of mix proportions

No.	Design strength (MPa)	Design slump (mm)	Water content kg/m^3	Cement content (kg/m^3)	Fine agg. content (kg/m^3)	Coarse agg. content (kg/m^3)
1	15	25–50	190	239	865	992
2	30	25–50	190	351	772	992
3	45	25–50	190	509	642	992

through resistivity, carbonation, alkalinity, and corrosion rates. For determining the compressive strength, 100 mm size cubical specimens were cast in triplicate. After 24 h, the specimens were demoulded and immediately kept immersed in the curing tank containing potable water. Specimens were removed from the curing tank, at the end of 1, 3, 7, 28 and 90 days. Test was carried out in a testing machine of 2000 kN capacity at a loading rate of 2.5 kN/s. From the failure load, the average compressive strength was calculated. Age factor was arrived at 1, 3, 7 and 90 day for blended cement concretes with respect to 28 days compressive strength of OPC concretes. The split tensile strength was conducted on cylinders (100×200 mm) at 28 days as per ASTM C 496-89.

Electrical resistivity of concrete is one of the important parameters in the study of the corrosion behaviour of steel in reinforced concrete members. Conversely, high electrical resistivity of concrete implies a high electrolytic resistance and this will limit the rate of corrosion [15]. The electrical resistivity of the concrete was measured by a direct two probe technique on 100 mm concrete cubes. Before starting the experiment the surfaces of the cubes were cleaned to remove any dust or loose material. By using high impedance digital meter the resistances were measured, on the wet surfaces of the cubes taken from normal water, whose values were used to find out the electrical resistivity of concrete depending upon the size of specimen.

The water phase in concrete normally has a pH within the ranges of 12.5–13.2. In this alkaline environment a thin passivating protective film is formed on the steel surface. However, this protective film is disrupted when the pH is reduced. Alkalinity reduces from 12.5 to around 9 due to penetration of atmospheric CO_2 into the concrete [16]. The addition of fly ash or slag in concrete may cause a reduction in pH due to pozzolanic reaction. The alkalinity or pH for all the concretes was studied through a representative sample from the middle of the cube (so as to avoid the effects of environmental ingress into the concrete). The sample, powdered and sieved through 300 μm mesh, was mixed with distilled water in the ratio of 1:5. After thorough mixing, the samples were closed with a tight lid and the pH values were measured with digital pH meter after 24 h. The pH was evaluated at 90 days.

Carbonation, which occurs due to the reaction between the carbon dioxide in the atmosphere and calcium hydroxide in concrete, can cause lowering of the pH to values below the corrosion threshold limit of 9.5, which may result in depassivation of steel and thus result in corrosion [17]. The depth of carbonation was measured on the split cylinder samples as suggested by CEB–FIP [18]. The split test was performed after 28 days curing in water. These broken samples were exposed to the outdoor atmosphere for a further period of 12 months. The specimens were broken across the length of the cylinder and the carbonation was measured immediately through the phenolphthalein indicator solution. The purple red portion indicates 'no carbonation' where as the colourless portion indicates the 'carbonation' depth. The carbonation depth was measured on both the surfaces at several points of at least two cross sections and the average values were reported.

Corrosion rate measurement is a reliable approach, which was used to investigate the corrosion process quantitatively. Corrosion rate of steel in concrete can be measured by weight loss, electrical resistance or electrochemical techniques. Among the electrochemical techniques, potentiodynamic (Tafel plot) and linear polarization techniques have been extensively used to study the rebar corrosion rates [19,20]. For the present investigation electrochemical potentiodynamic polarization technique was adopted to measure corrosion rates on 8 mm diameter and 230 mm long rebars embedded centrally with 100 mm exposed portion in 100×200 mm concrete cylinders (as shown in Fig. 1) by using a scanning potentiostat (EG&G PAR Model 362) and a X-log X, Y recorder (EG&G PAR – Model RE 0092). A potential of 250 mV was applied on either side of open circuit potential (OCP) and the corrosion current (I_{corr}) was taken from the tangents drawn at 100 mV from the potentiodynamic plot. In all the tests a scan rate of 1 mV/s was selected. The high sweep rate was selected to avoid the occurrence of potential shifts (especially for con-

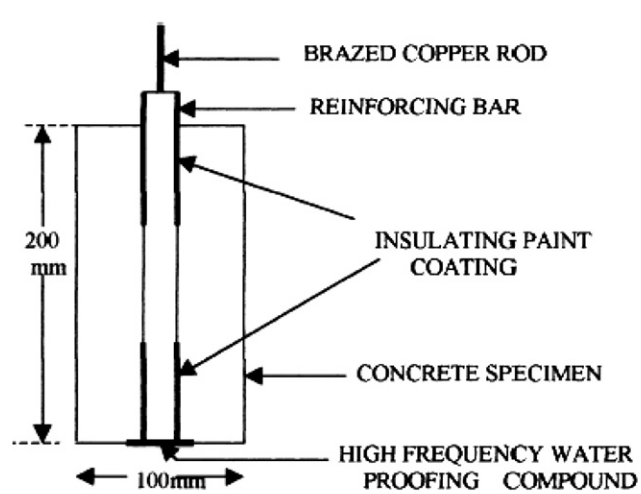

Fig. 1. Typical cylindrical specimen with steel inside.

cretes with mineral admixtures – this had been observed previously in our laboratory in a number of cases). The corrosion rate was calculated from this I_{corr} by using Faraday's equation [21]. The corrosion rates were evaluated at 90 days for both normal and sea- water immersion specimens. The sample was immersed in 3% NaCl solution for 4 days before the actual test was performed for conditioning.

3. Results and discussion

3.1. Workability and strength

The workability and strength results are included in Table 3. It can be seen that almost all the concretes had the design slump, but for a few exceptions, mostly in blended cement concretes. However, all the concretes could be easily compacted with the needle vibrator for compaction. The variation of the compressive strength with age up to 90 days for all the concretes were studied through the age factors. The results show that the age factor increases with curing period and the grades of concrete have marginal effect on age factor. It can be seen that as the age increases the compressive strength also increases, for all the concretes. At the early ages both PPCs and BFSCs showed slightly lower strengths than the corresponding OPCs. This initial lower strength was due to the slower rate of hydration in PPCs and BFSCs, with increase in age the pozzolanic reaction increases and consequently the strength increases. This resulted in slightly higher strengths both at 28 and 90 days than the corresponding OPCs. The split tensile strength test was done after 28 days of curing and the results are also presented in Table 3. Fig. 2 shows the variation of the split tensile strength with compressive strength. From this it can be seen that the relationship is the same for all the concretes, irrespective of the type of cement.

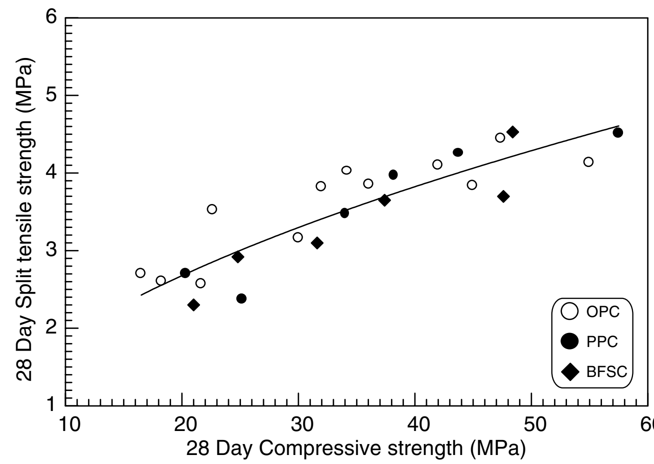

Fig. 2. Variation of split tensile strength with compressive strength.

Table 3
Workability and strength results of the concretes investigated

Cement type	Grade	Slump (mm)	Compressive strength					Split tensile strength 28 day
			28 day (MPa)	Age factors				
				1 day	3 day	7 day	90 day	
OPC-1	M 15	25	16.5	0.24	0.45	0.727	1.14	2.71
	M 30	13	32.0	0.40	0.584	0.80	1.143	3.82
	M 45	20	42.0	0.438	0.66	0.823	1.078	4.11
OPC-2	M 15	18	21.6	0.509	0.722	0.940	1.13	2.58
	M 30	95	36.0	0.455	0.736	0.888	1.11	3.85
	M 45	65	55.0	0.492	0.736	0.796	1.109	4.13
OPC-3	M 15	25	18.2	0.35	0.609	0.725	1.15	2.6
	M 30	14	30.0	0.40	0.72	0.873	1.146	3.17
	M 45	80	45.0	0.384	0.626	0.76	1.128	3.84
OPC-4	M 15	35	22.6	0.451	0.619	0.761	1.216	3.52
	M 30	48	34.2	0.38	0.649	0.795	1.181	4.03
	M 45	35	47.4	0.502	0.67	0.843	1.033	4.45
PPC-1	M 15	30	20.3	0.256	0.502	0.68	1.064	2.70
	M 30	65	34.0	0.23	0.417	0.655	1.08	3.48
	M 45	30	43.7	0.36	0.604	0.812	1.08	4.26
PPC-2	M 15	10	25.2	0.34	0.547	0.642	1.126	2.38
	M 30	40	38.2	0.437	0.609	0.824	1.05	3.97
	M 45	25	57.5	0.471	0.58	0.79	1.078	4.52
BFSC-3	M 15	30	25.0	0.252	0.533	0.809	1.119	2.3
	M 30	40	31.6	0.382	0.667	0.80	1.12	3.10
	M 45	15	47.6	0.386	0.636	0.827	1.067	3.70
BFSC-4	M 15	45	24.8	0.25	0.50	0.806	1.17	2.92
	M 30	45	37.4	0.342	0.53	0.77	1.096	3.65
	M 45	35	48.4	0.451	0.648	0.74	1.033	4.53

3.2. Electrical resistivity studies

The resistivity values at different ages for both PPCs and BFSCs with their corresponding OPCs are shown in Table 4. From this it can be seen that the resistivity of concrete increases with age and also with the strength of the concrete. Both PPCs and BFSCs have shown more electrical resistivities than the corresponding OPCs at 28 and 90 days. At the initial ages both PPCs and BFSCs showed lower electrical resistivities, and it was also found that the rate of increase of resistivity was high between third and 28 days. This may be attributed due to the pozzolanic effect, which generally starts from the third day onwards. The improvement in the resistivity of pozzolanic concrete was due to the combination of filler and pozzolanic effects, which results in the pore refinement and higher density. In a similar study Hansson and Hansson [22] studied the electrical resistivity measurements of Portland cement based materials. They found that as the age increases the resistivity also increases due to the reduction of pore size by pozzolanic reactions in blended cements. The electrical resistivity of both PPCs and BFSCs with respect to their corresponding OPCs at 90 days are shown in Fig. 3. From this it can be observed that as the grade of concrete increases the resistivity also increases, and also the fly ash and slag concretes showed more electrical resistivity than the corresponding OPCs. The limitations given by Browne et al. [23] were also shown in the same figure. All the concretes developed with OPCs, PPCs and BFSCs showed the probable corrosion rates as negligible, showing electrical resistivity more than 20 kΩ cm. In an earlier study Hope et al. [24] also reported that, in general, concretes having electrical resistivity over 30 kΩ cm did not exhibit evidence of severe corrosion. The variation of resistivity with compressive strength is presented in Fig. 4. From this it can be seen that as strength increases the electrical resistivities also increases correspondingly. Compared to OPCs the increase of electrical resistivity in the case of blended cements was found to be steep with slag cements showing higher electrical resistivity values. Similarly Hope and Ip [25] investigated the electrical resistivity of slag at 75% and 50% replacement and found that after 7 days of curing the electrical resistivity of slag at the above replacements gain more resistivity with age compared to normal Portland cement concretes. Gjorve [26] found that, by reducing w/c ratio from 0.7 to 0.5 the resistivity of the mortars was more than doubled. For a w/c ratio of 0.5 the resistivity of mortar was more than three times higher than that of the concrete, which indicates the effect of the maximum aggregate size. Lopez and Gonzalez [27] studied the influence of the degree of pore saturation on the electrical resistivities of concrete and found that it has a very strong effect on the

Table 4
Corrosion characteristics of the concretes investigated

Cement type	Grade	Electrical resistivity (kΩ cm)			pH	CD (mm)	Corrosion rate (mpy)	
		7 day	28 day	90 day			NW	SW
OPC-1	M 15	31.27	34.15	32.50	12.50	16.0	1.0	1.4
	M 30	31.14	35.40	35.70	12.37	11.0	1.5	1.9
	M 45	30.20	38.66	38.15	12.00	2.0	1.4	1.3
OPC-2	M 15	21.75	30.00	40.40	12.23	7.28	2.6	5.8
	M 30	23.80	22.30	43.60	12.17	6.28	1.6	3.6
	M 45	26.70	39.20	47.20	12.23	1.40	1.7	2.8
OPC-3	M 15	30.50	32.80	33.90	12.20	7.0	1.9	2.4
	M 30	29.20	38.20	41.70	12.23	6.05	1.5	1.9
	M 45	35.40	42.00	46.90	12.20	5.90	0.3	1.9
OPC-4	M 15	14.30	27.80	36.40	12.30	5.57	2.7	3.3
	M 30	24.30	36.70	42.30	11.90	4.45	2.4	2.4
	M 45	34.00	41.20	43.60	12.35	2.0	2.3	1.8
PPC-1	M 15	28.78	28.10	34.20	12.06	14.10	0.8	0.8
	M 30	30.62	40.00	43.80	11.90	5.71	0.7	0.9
	M 45	41.60	47.40	50.50	12.10	2.0	0.7	0.9
PPC-2	M 15	18.83	39.43	40.70	12.21	13.73	1.7	2.1
	M 30	23.00	47.48	47.80	12.20	5.51	1.2	2.3
	M 45	23.23	41.40	51.15	12.22	1.20	1.0	2.2
BFSC-3	M 15	27.60	55.55	50.15	12.00	11.94	0.09	0.5
	M 30	34.00	49.00	51.95	12.09	10.40	0.07	0.4
	M 45	36.85	50.90	55.15	12.10	5.24	0.08	0.3
BFSC-4	M 15	25.30	39.10	43.40	12.20	7.60	0.30	0.4
	M 30	36.80	41.40	45.70	12.29	5.47	0.40	0.5
	M 45	32.20	43.30	46.10	12.42	6.92	0.39	0.4

NW, normal water immersion; SW, sea water immersion; CD, carbonation depth; and mpy, mills per year (1 mpy = 0.0254 mm/year).

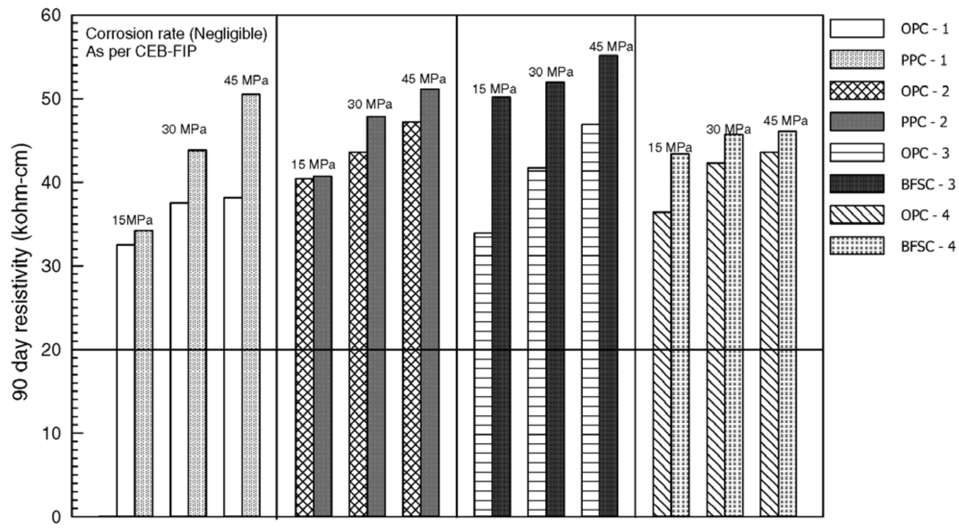

Fig. 3. Comparison of electrical resistivity values.

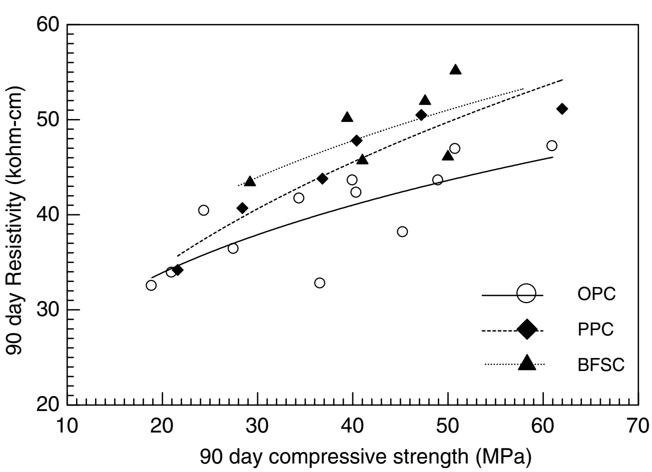

Fig. 4. Variation of electrical resistivity with compressive strength.

corrosion kinetics. In another study Hussian and Rasheeduzzafar [20] investigated the electrical resistivity on concretes with 30% fly ash at a w/c of 0.5 and a cement content of 350 kg/m^3. The resistivity for fly ash concretes was found to be 29 kΩ cm after 120 days and which was about 2.2 times more than the corresponding plain cement concretes.

3.3. Alkalinity studies

The results of the pH of all the concretes developed with various cements are included in Table 4. From the table it can be observed that almost all the concretes were well above the limit (12.0) for depassivation showing no ill effects of the alkalinity reduction due to the pozzolanic reactions even in the BFSC concretes containing 50% slag and also all these values were above the threshold limit of 9.5 as recommended by Hobbs [17] for depassivation. It was also observed that the grade of concrete had no specific effect on the alkalinity as indicated earlier by Babu and Rao [28]. Likewise Byfors [29] studied the pore solution of 40% fly ash cement pastes and indicated that the pH reduction was negligible for the above paste. In an earlier study Al Amoudi et al. [30] showed that a direct replacement level up to 40% fly ash in concrete lowered the values of pH only to around 12.5.

3.4. Carbonation studies

In general, blending of fly ash or slag may influence carbonation depths. These data are presented in Table 4. From this table it can be seen that the effects of carbonation will be lower at higher strength due to lower porosity and permeability and also the carbonation depths decrease with increasing strength. Between PPCs and the corresponding OPCs the pozzolanic addition is felt mostly in lower strength concretes and concretes of higher strength (about 45 MPa) the carbonation was almost the same. Between BFSCs and their corresponding OPCs it was observed that BFSCs have shown more carbonation depths than their corresponding OPCs in all grades. The reason may be, that blending of cement with mineral admixtures leads to a lowering of $Ca(OH)_2$ content in the hardened cement paste so that a smaller amount of CO_2 is required to remove all the $Ca(OH)_2$ by producing $CaCO_3$ [31]. The depth of carbonation was in the range of 1.4–16.0 mm in case of OPCs whereas the corresponding PPCs showed depths in the range 1.2–14.1 mm. Similarly between OPCs and the corresponding BFSCs, OPCs showed the carbonation depths in the range 2.70–7.0 mm whereas in BFSCs the carbonation depths are in the range of 5.24–11.94 mm. In a study carried out by Vagelis et al. [32] it was shown that the adverse affect of pozzolan, which was used for replacement of cement on the carbonation, had favourable effect on porosity. The depth of carbonation could be related to intrinsic permeability, the rate of carbonation was most significantly influenced by the free water cement ratio and the period of moist curing and changes in cement content, workability and aggregate size do not have a marked effect on carbonation resistance of concrete [33]. In a similar investigation Torii and Kawamura [34] also studied the depth of carbonation of concretes both with and without mineral admixtures exposed to different environmental conditions after initial curing period of 7 or 28 days, over a period of one year. They reported that carbonation depth values were very sensitive to exposure conditions, the carbonation depth values for all the concretes increase in following environment exposure conditions, i.e., 60% RH indoor storage > outdoor exposure > storage in water. They noted that the carbonation depth increased with increasing water cement ratio and decreasing with the period of initial curing. It was noted that depth of carbonation of concrete with mineral admixtures was much higher than that of the corresponding OPC concretes both at dry and wet curing conditions. In particular, 50% slag concretes showed higher carbonation depth compared to OPC. Typical values of carbonation depth for slag concretes cured initially in water and exposed to dry environment for one year was 1.3 mm, the corresponding value for OPC concrete was 0.2 mm.

3.5. Corrosion rate studies

The corrosion rates of OPCs with respect to their corresponding PPCs and BFSCs for both normal and seawater immersion specimens are shown in Figs. 5 and 6. From theses figures it can be seen that PPCs performed better in all the grades of concrete both in normal water and seawater immersion than the corresponding OPCs. Whereas, the corrosion rates in BFSCs are about 8–20 times lower than their corresponding OPCs. This may be due to higher blending, low diffusivity and high resistivity of these concretes which limits severely the corrosion. In a similar investigation Maslehuddin et al. [35] also observed that the corrosion rates of the reinforcing steels in pozzolanic cement and blast furnace slag cement concrete exposed to NaCl solution for more than 5 years found to be lower than those in plain and pozzolanic cement concrete specimens. It can also be seen that the corrosion rates of all slag cement concretes and some of the fly ash cement concretes were below 1 mpy which shows that all these concretes come under excellent category in resisting corrosion [36]. The grade of concrete had a minimal effect on the corrosion rates of blended cements as can be observed from Fig. 7. There was a very marginal decrease of corrosion rates as the grade of concrete increases; it is only the percentage replacement of pozzolan that determines the effect. Similar trend was also found to be seen in the case of resistivity with respect to corrosion rates (Fig. 8). However, in the case of BFSCs a better trend was found.

On the other hand, between PPCs, PPC-1 offered better corrosion resistance than PPC-2, and between BFSCs, BFSC-3 offered good resistance both in normal and seawater exposure. The corrosion rates in normal water immersion specimens are lower than seawater immersion specimens. This may be due to the presence of corrosive species like chlorides, etc. in sea water. Patil and Gajendragad [37] also reported that sea water mixed and cured samples showed higher corrosion rates than the similar water mixed and cured specimens. In another investigation Al-Tayyib and Khan [19] studied the corrosion rates of reinforcing steel in concretes (w/c of 0.40, 0.55 and 0.70) through the electrochemical techniques (Tafel plot and linear polarization) and weight loss method. The concretes were exposed to 5% NaCl solution and the corrosion rates were measured after 2 years. The average corrosion rate of the reinforcing steel bars in concretes with the above water cement ratios as determined by Tafel plot are found to be

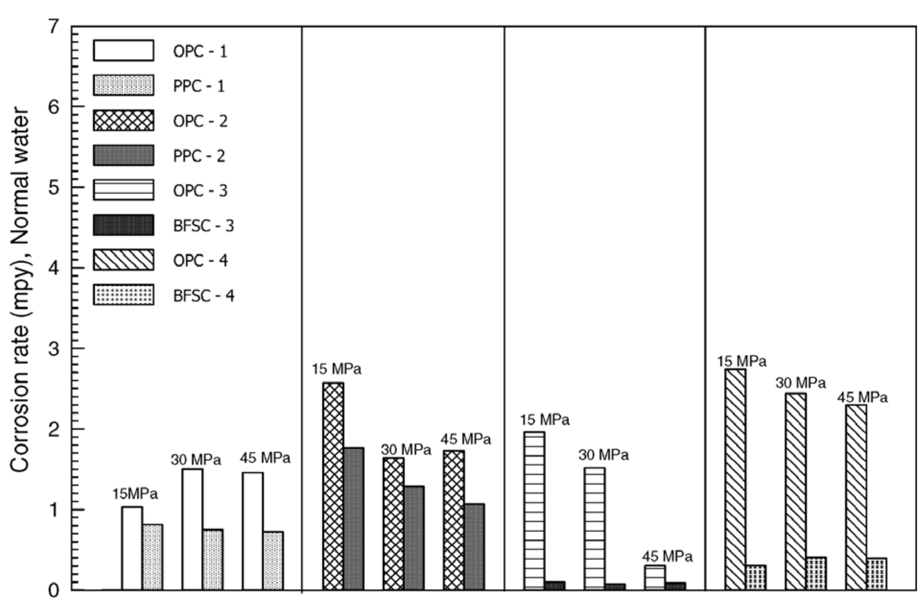

Fig. 5. Corrosion rates of the concretes investigated (normal water immersion).

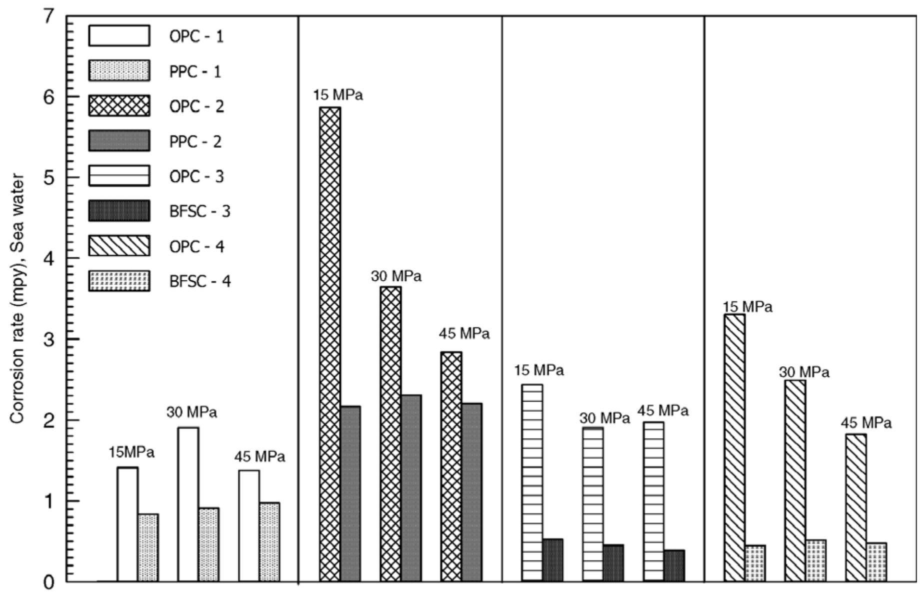

Fig. 6. Corrosion rates of the concretes investigated (sea water immersion).

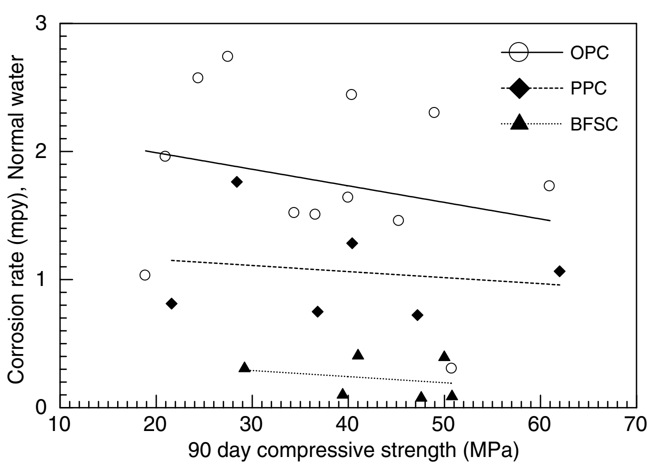

Fig. 7. Variation of corrosion rate with compressive strength.

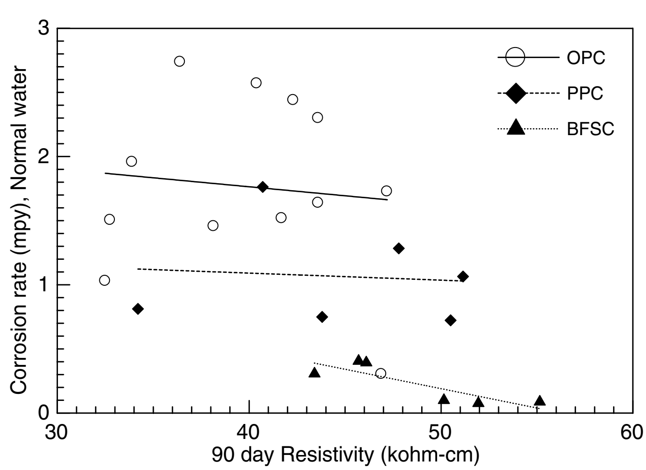

Fig. 8. Variation of corrosion rate with electrical resistivity.

0.68, 1.93 and 3.03 mpy respectively. In a study carried out by Maslehuddin et al. [38] at different cement contents with the same 20% replacement, fly ash showed lesser corrosion rates than the corresponding plain cement concretes after 1000 days exposure to 5% NaCl solution. In a similar type of study Hussain and Rasheeduzzafar [20] studied the corrosion rates of 30% fly ash concrete and reported 0.97 mpy after 1200 days of exposure to 5% NaCl solution. Mangat et al. [39] investigated the corrosion rate characteristics of concretes made with 20% pulverized fuel ash, 10% microsilica and 40% blast furnace slag at 0.58 water cement ratio. They reported the values of corrosion rates as 0.00754 mm/year for no replacement and 0.018 mm/year for pulverized fuel ash and 0.0047 mm/year for microsilica and 0.0054 mm/year for blast furnace slag concretes.

In general, data developed in this investigation show that the corrosion rates of reinforcing steel in concrete specimens containing blast furnace slag cements and Portland pozzolana cements are lower than the corresponding ordinary Portland cements. This indicates that where durability of concrete against chloride ingress is the primary criterion, these blended cements can be used to produce dense concrete.

4. Conclusions

1. The compressive strengths of PPCs and BFSCs at both 28 and 90 days were marginally higher than the corresponding OPCs though at the early age strengths were marginally lower. The relationships between compressive strength and tensile strength evaluated show that the cement type did not exhibit any bearing on the relationship.
2. The resistivities of the concretes show that both PPCs and BFSCs have marginally higher values than their corresponding OPCs at 28 and 90 days. This may be due to pozzolanic effects, which results in the pore refinement and higher density. All these concretes were

also showing resistivities above 20-kΩ cm the limit set for good concretes according to the limitations given by Browne et al. [23].

3. The alkalinities of PPC and BFSC concretes were not significantly lower than the OPC concrete. The pH in all the concretes was observed to be in the range 12.0–12.5, which is above the threshold value of 9.5 suggested by Hobbs [17] for depassivation. However, the carbonation depths of BFSCs were slightly higher than their corresponding OPCs. PPCs and their corresponding OPCs performed almost similarly, this may be due to the lesser amount of blending of fly ash (20%) in both the PPCs. Neville [31] also reported that blended cements would lead to higher carbonation. The carbonation depths decreased significantly with increasing strength grades of concretes as observed by Kokubu and Nagataki [40].
4. PPCs and BFSCs have shown lower corrosion rates than the corresponding OPCs. This effect was quite significant in BFSCs than PPCs. Between OPCs and PPCs, OPCs showed corrosion rates in the range 5.8–1.3 mpy whereas the corresponding PPCs showed the corrosion rates in the range 2.3–0.8 mpy. The corrosion rates in BFSCs are about 8–20 times less than the corresponding OPCs. The corrosion rates are in the order: BFSCs < PPCs < OPCs.
5. In conclusion, it is evident that concretes with BFSCs have performed significantly better than not only the corresponding OPCs, but are also better than other PPCs. This can be mainly attributed to the fact that the slag replacement level is as high as 50% resulting in a higher chloride binding capacity while still retaining the pozzolanic reactivity at this high percentage replacement. However, the carbonation is higher in these concretes as expected. But this is only a problem in lower strength concretes and at higher strengths these are as good as that for other cements.

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