BOND STRENGTH AND CORROSION RESISTANCE OF REINFORCED CONCRETE EXPOSED TO SIMULATED ACIDIC AND ALKALINE MARINE ENVIRONMENT

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ABSTRACT. This research investigates the potentiality of reinforced concrete exposed to acidic and alkaline marine environment. The potential was measured with respect to corrosion rate and ultimate bond strength of reinforced concrete produced with three different types of cement, ordinary Portland cement (OPC), Portland pozzolana cement (PPC) and Portland slag cement (PSC). Five types of curing periods (7, 14, 28, 56 and 90 days) were chosen to study the effect of prolonged curing. The durability studies such as compressive strength loss, corrosion resistance, and bond strength retention were performed after exposing the samples to acidic and alkaline marine environment. The regression analysis showed a meaningful relationship between compressive strength and ultimate bond strength of reinforced concrete. The prolonged curing has positive influence on compressive strength and ultimate bond strength development of PPC and PSC concrete. After 90 days of curing, PSC concrete mix showed 7.4% and 2.1% higher ultimate bond strength values than OPC and PPC concrete respectively. From exposure studies it was observed that corrosion rates were lowest in PSC concrete. The performance of PSC concrete was better with respect to compressive strength retention and bond strength retention in acidic as well as alkaline marine environment compared to PPC and OPC concrete. After 90 days of exposure to acidic marine environment the PSC concrete had 90% bond strength retention, whereas, OPC and PPC concrete had 74% and 86% respectively.

Keywords: Cement types, Compressive strength, pH, Bond strength retention, Corrosion resistance.

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INTRODUCTION

One of the crucial challenges for the civil engineering community in recent years is assessing, monitoring and then controlling the deterioration of reinforced concrete structures in aggressive environments such as marine environment [1–3]. Among the multi-facet phenomena of deterioration of concrete, corrosion of reinforcement can be considered a vital one [4] and has drawn great attention in the present time. The initiation of corrosion of reinforcement in reinforced concrete gives an understanding that the designed concrete of required quality fails to provide adequate protection against environmental conditions in which the structure is in service [5,6]. There can be numerous reasons that lead to the initiation of corrosion in reinforced concrete structures before the designed service life. Some of them are, use of already corroded reinforcement during construction, higher water/cement ratio or curtailed amount of cement, inadequate concrete cover, poor compaction of fresh concrete during casting, poor resistance of concrete against the penetration of water, salts and CO2, acid rain, unnecessary contact of concrete with contaminated salts, sulphates or any harmful agents [7–9]. With respect to chemical industries near the coastal region, which release harmful liquids to the sea and gases directly into the atmosphere, it is seen that over a period of time, acidic compounds deposit on the surface of the concrete structure and in the presence of moisture, start their ingress into the concrete [5]. The pH of acidic compounds which deposit on the concrete surface may vary from 2.5 – 3.5. In extreme conditions such as direct disposal of chemical residue through sewer pipes, the concrete may be subjected to a pH of 1.5 – 2.5 [10]. The acidic compounds deteriorate the concrete which makes ease for other harmful agents such as chlorides and moisture to disseminate inside the concrete structures. Once the harmful ions reach the steel surface in reinforced concrete, the corrosion process initiates which leads to deterioration of concrete structures. When corrosion initiates in reinforced concrete structures, it progresses at a steady rate causing expansion of steel reinforcement which results in surface cracking and spalling of cover concrete and ultimately shortens the service life of structures [11,12]. Another ill effect of corrosion is that it reduces the bond strength between steel and surrounding concrete. It was reported by Fang [13] that during the initial stages of corrosion, corrosion products start to accumulate along the periphery of the steel bar and pores at steel-concrete interface which increases friction between reinforcing steel and surrounding concrete resulting in an increase of bond strength. However, as the corrosion rate increases, corrosion products start to exert expansive pressure and when the expansive pressure is greater than the tensile strength of concrete, corrosion cracks will be induced and bond strength between steel and concrete will reduce considerably [14]. The corrosion cracks not only reduce the bond strength, but they also provide an easy access to harmful ions to penetrate into the concrete which reduces the durability of reinforced concrete structures [15].

Corrosion resistant reinforcement bars and metallic coatings, organic coatings, and a better understanding of concrete control are some of the modern developments invented by scientists in controlling the corrosion of reinforcement in concrete [16–18]. Further, it was noticed that researchers and scientists over time, developed different kinds of cement which were found to be durable and applicable to the specific harsh environment. A few being for example, sulphate resistant cement, low heat cement, rapid hardening cement, hydrophobic cement, PPC, PSC and many more [19]. PPC and PSC are by far found to be the best replacement for OPC in an aggressive environment because of their eco-friendly nature and also enhanced durability properties [20,21]. Many research articles report that PPC and PSC concrete are better corrosion resistant in one kind of harsh environment such as marine environment [22,23]. The present investigation aims to find the potentiality of OPC, PPC and

PSC concrete when exposed to multi-aggressive environment such as acidic and alkaline marine environments. The potentiality OPC, PPC and PSC concrete was measured with respect to corrosion resistance, bond strength retention and compressive strength retention. The effect of reinforcement corrosion on bond strength between steel and concrete was also studied.

METHODOLOGY

Materials used and their Properties

The physical and chemical properties of OPC, PPC, and PSC used in the present study are tabulated in Table 1. The natural silicious river sand and crushed granite were used as fine aggregate and coarse aggregate respectively and their specific gravities were 2.56 and 2.63 respectively.

Table 1 Physical and chemical properties of cements used in the present investigation

COMPOUND	OPC (%)	PPC (%)	PSC (%)
SiO_2	20.5	29.2	27.5
Al_2O_3	5.3	9.6	10.5
Fe_2O_3	4.6	4.0	3.2
CaO	62.2	43.5	45.6
MgO	0.8	1.2	3.5
SO_3	2.3	2.6	2.0
LOI	2.3	2.6	2.0
Specific gravity	3.15	2.90	3.03
Fineness (cm^2/kg)	3000	3433	3600

Mix Proportions of Concrete

All concrete mixes were designed according to the specifications of IS: 10262-2009 to produce M40 grade concrete with w/c ratio of 0.4. The details of concrete mix proportions are given in Table 2. The same mix proportion was followed for production of OPC, PPC and PSC concrete. The coarse aggregates used were of 20 mm MSA (maximum size of aggregate). Natural river sand was used as fine aggregate. In order to maintain workability of concrete at slump range of 75-85 mm, superplasticizer (PC based, Master Glenium 51) was used.

TEST DETAILS

The details of tests conducted such as bond strength, compressive strength, exposure to a marine environment with acidic and alkaline exposure conditions, compressive strength retention and bond strength retention and corrosion resistance are described in the following sections.

Table 2 Mix proportion of concrete

CONCRETE MIXTURE PROPORTIONS				
Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	SP
152	380	816.64	1104.77	0.5%

-SP designates to superplasticizer (0.5% of cement content)

Measurement of bond strength

To assess the bond strength, cubical specimens of size 100 × 100 × 100 mm were prepared and provision was made to place a single ribbed reinforcement bar (Fe 500) at the centre of the cubical specimen as presented in Figure 1. The ultimate bond strength was measured by pullout test according to the specifications given in [24].

Measurement of compressive strength

Cubical specimens of size 100 × 100 × 100 mm were prepared and were tested for compressive strength measurement at different curing periods. In addition, the same size of specimens were also tested for compressive strength loss against the marine environment with acidic and alkaline exposure conditions which is expressed in compressive strength retention at a later point of time. The curing durations such as 7, 14, 28, 56 and 90 days were considered in the present investigation. The compressive strength test was carried out according to the specification given in [25].

Exposure to marine environment with the acidic and alkaline condition

The effect of the multi-aggressive environments such as a marine environment with acidic and alkaline exposure conditions on corrosion resistance and bond strength of reinforced concrete produced with OPC, PPC, and PSC was studied. The acidic exposure condition with the marine environment was created by adding a calculated quantity of normalized sulphuric acid and 3.5% NaCl to tap water. Two concentrations of acidic exposure conditions were prepared, namely a strong acid solution with pH 1 and mild acid solution with pH 4 [26–29]. The alkaline exposure condition with the marine environment was created by adding a calculated quantity of normalized sodium hydroxide solution and 3.5% NaCl to tap water. Two concentrations of alkalinity were prepared, namely strong alkaline condition with pH 13 and mild alkaline condition with pH 10.

Further, the OPC, PPC and PSC concrete samples after 28 days of water curing were exposed to acidic exposure with the marine environment (pH 1 and pH 4), marine environment (pH 7) and alkaline exposure with the marine environment (pH 10 and pH 13) for a period of 30 and 90 days. Once the desired duration of exposure was completed, the samples were removed from aggressive media and kept for surface drying for at least four hours before testing.

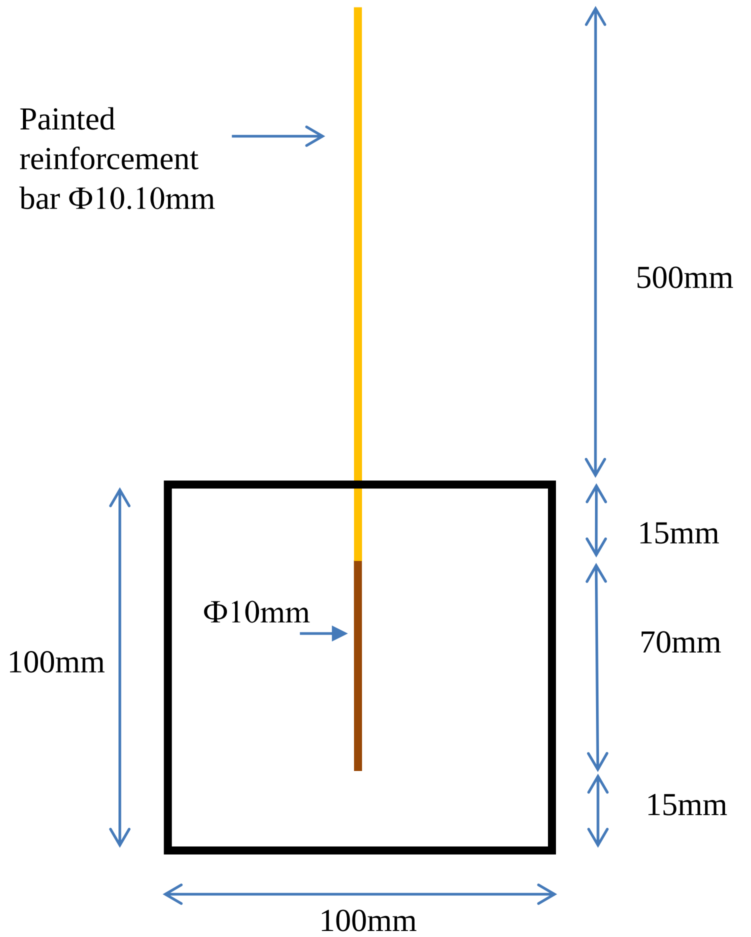

Figure 1 Schematic representation of the sample used for corrosion and bond strength measurement

Determination of compressive strength retention and bond strength retention

For better understanding, the concept of strength retention was used. After the exposure period, each set of samples was tested for change (decrease/increase) in the compressive strength/ultimate bond strength and compared with their controlled values. The compressive strength/ultimate bond strength values of controlled specimens were treated as 100% strength retention. If the strength retention value was less than 100% than the controlled one, it indicates a reduction in strength because of exposure to the aggressive environment. Similarly, if the value was found to be more than 100%, it indicates that there was a strength gain. The values of compressive strength/bond strength retention represented in the present study were averages of three samples.

Measurement of corrosion resistance

Once the desired exposure period was completed, the cubes with reinforcement bar were taken for corrosion analysis. Before going for LPR measurement, the change in potential of reinforcement bar after exposing to the aggressive environment was measured by open circuit potential (OCP). Saturated calomel electrode was used as a reference electrode in open circuit potential test. After the OCP, the same set of samples were studied for the rate of corrosion through linear polarization resistance (LPR) technique. A potential of 20 mV was applied and then maintained throughout the experiment.

RESULTS AND DISCUSSION

Compressive Strength Development of OPC, PPC and PSC Concretes

Figure 2 presents the compressive strength of OPC, PPC and PSC concrete mixes cured for 7, 14, 28, 56 and 90 days. Compressive strength increased in parallel with the increase in curing periods for all the mixes. However, the compressive strength of PPC and PSC concrete mixes were lower during the initial curing periods compared to OPC concrete mixes, which can be attributed to faster hydration rate of OPC mixes compared to PPC and PSC concrete mixes [22]. However, as the curing period increased beyond 28 days, because of pozzolanic reaction, the strength gains of PPC and PSC concrete mixes were comparable to OPC concrete mixes. If 28 days of water curing is considered as a reference point for strength indicator, OPC concrete mixes had 5.9% and 11.7% higher compressive strength than PPC and PSC concrete mixes respectively. Whereas, at 90 days of water curing, the compressive strength of OPC concrete mixes was only 1.9% and 3.9% higher than that of PPC and PSC mixes.

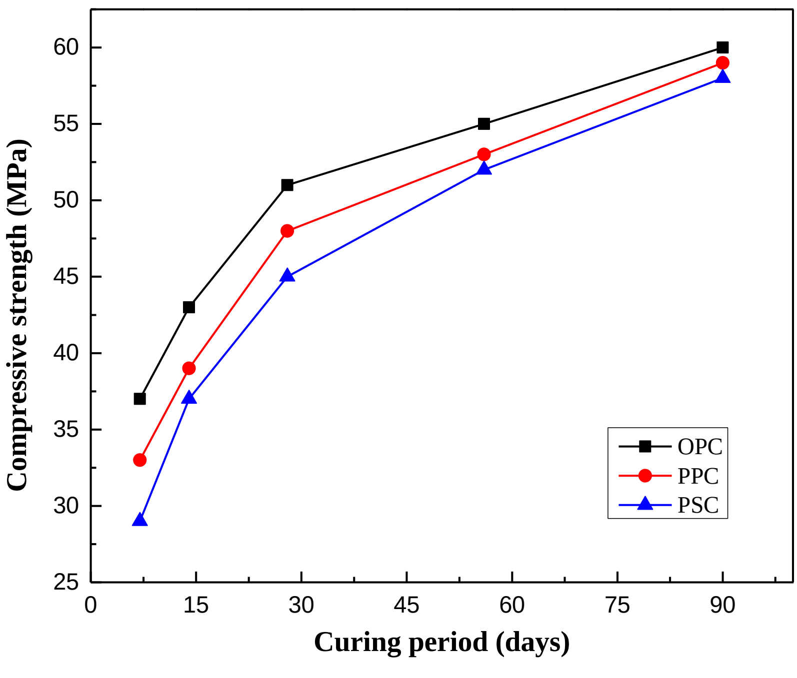

Figure 2   Compressive strength development with respect to curing period

Ultimate Bond Strength of OPC, PPC and PSC Concretes

Figure 3 presents the ultimate bond strength of OPC, PPC and PSC concrete mixes cured for 7, 14, 28, 56 and 90 days. It has been observed that the curing period has a significant influence on the ultimate bond strength of reinforced concrete. At 28 days of water curing, all the mixes had similar ultimate bond strength values, but the prolonged curing of PPC and PSC concrete mixes showed significant improvement in ultimate bond strength. As the curing period increased from 7 to 90 days, an increase in ultimate bond strength of 23.5%, 38.8%, and 45.3% was observed for OPC, PPC, and PSC concrete mixes respectively. The higher percentage of bond strength gain for PPC and PSC mixes can be attributed to the fineness of cement particles as well as pozzolanic reaction. At 90 days of curing, PSC concrete mixes showed 7.4% and 2.1% higher ultimate bond strength than OPC and PPC concrete mixes.

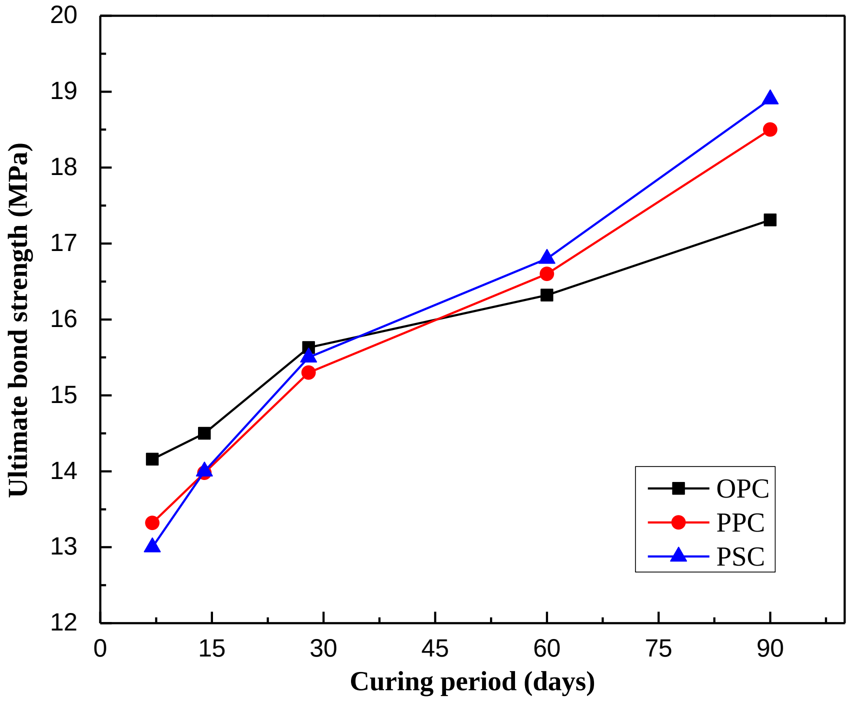

Figure 3   Ultimate bond strength development with respect to curing period

Effect of Acidic and Alkaline Exposure with Marine Environmental Condition On Compressive Strength, Corrosion Resistance and Bond Strength of OPC, PPC, and PSC Concretes

Compressive strength retention of OPC, PPC and PSC concrete mixes

The compressive strength retention after 30 and 90 days of exposure to aggressive environments are presented in Figure 4. When the specimens were subjected to acidic and alkaline exposure in the marine environment for a period of 30 days and 90 days, the compressive strength of the cubes reduced considerably. Exposure period and pH of the marine environment played a decisive influence on the compressive strength retention of all the mixes. As pH of the marine environment increased (from acidic, pH 1 to basic, pH 13), compressive strength retention was found to be increasing as alkaline exposure is less detrimental. Because of the acid exposure especially at pH 1, OPC concrete mixes had a compressive strength retention of 84.2% and 76.12% for 30 and 90 days of exposure respectively. However, PSC and PPC concrete mixes had better compressive strength retention compared to OPC concrete mixes. The alkaline marine environment (pH 10 and 13) was found to be less detrimental compared to neutral marine environment (pH 7). This signifies that the migration of chloride ions was hindered by hydroxyl ions of sodium hydroxide in alkaline marine environment. It can also be observed that exposure to pH 13 has slightly higher compressive strength retention values compared to pH 10. Out of these three concrete mixes, PSC concrete proved to be better resistant to the harsh aggressive environment with respect to compressive strength retention even after 90 days of exposure.

Corrosion behaviour of OPC, PPC, and PSC concretes exposed to acidic and alkaline marine environment

After 28 days of water curing, open circuit potential (OCP) of OPC, PPC, and PSC concrete were found to be -322.43 mV, -319.29 mV and -333.72 mV respectively. It is to be noted that OCP only gives a gross idea about the possibility of corrosion occurrence and fails to provide the actual corrosion potentials [26,30].

Absolute corrosion current (Icorr) and corrosion potential (Ecorr) of rebar were measured by linear polarization resistance (LPR) technique [5]. The Ecorr values of OPC, PPC, and PSC concrete after 28 days of water curing are presented in Table 3. The Ecorr values of OPC, PPC and PSC samples exposed to acidic marine environment (pH 1 and pH 4) and alkaline marine environment (pH 10 and pH 13) for a period of 30 and 90 days are graphically presented in Figure 5. The corrosion rates were calculated from the data measured through LPR technique and the values are graphically presented in Figure 6.

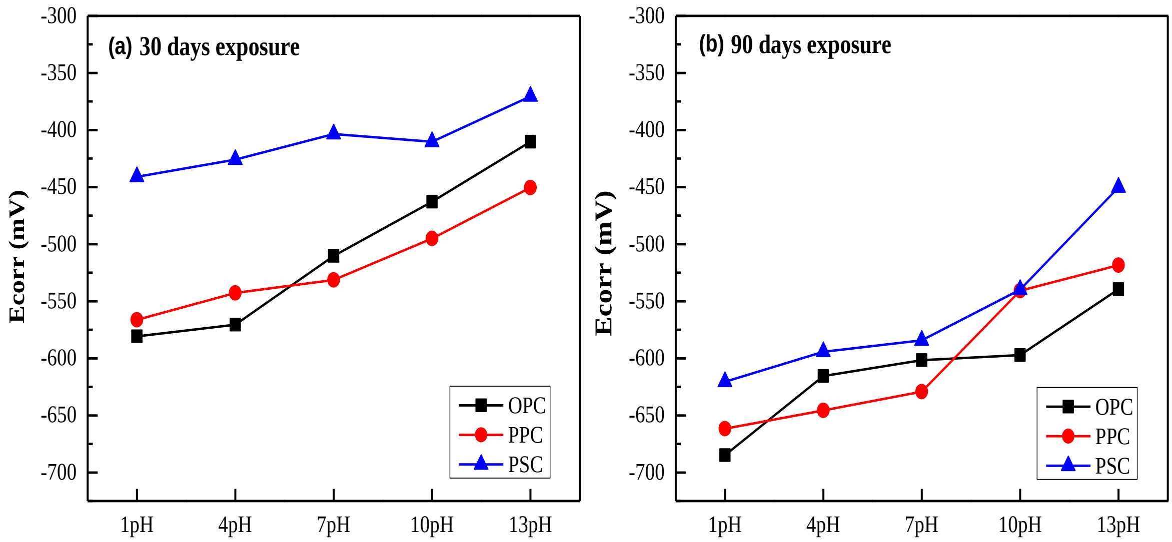

Figure 5 Corrosion potential of samples subjected to acidic (pH 1 and pH4) and alkaline (pH 10 and pH 13) exposure condition in the marine environment for different duration.

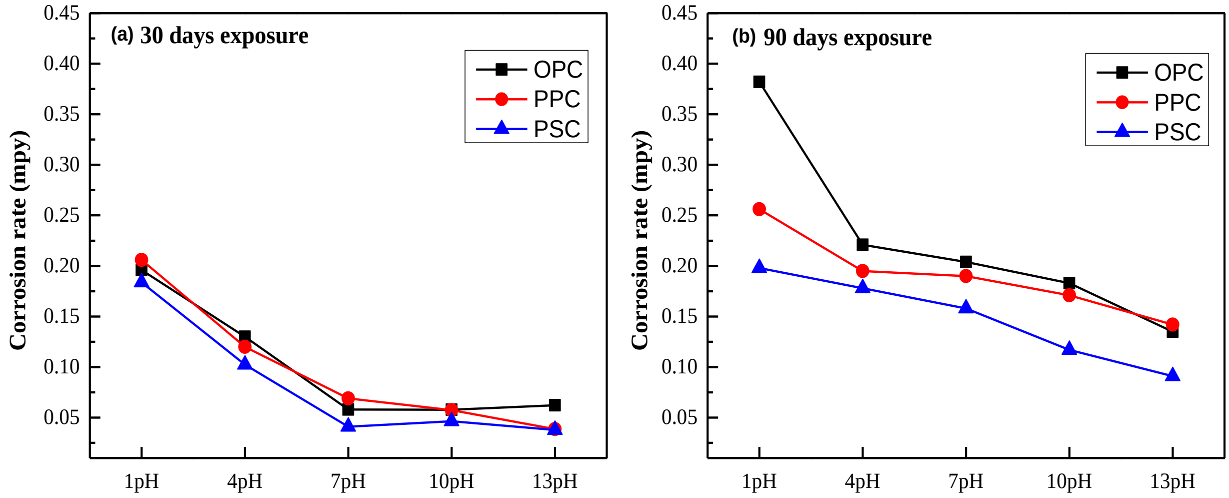

Figure 6 Corrosion rate of samples subjected to acidic (pH 1 and pH4) and alkaline (pH 10 and pH 13) exposure condition in the marine environment for different duration.

It is to be noted that higher the negative value of corrosion potential (Ecorr), greater is the chance for a sample to corrode [29]. It can be observed from Figure 6 that with pH of the exposure condition (from acidic, pH 1 to basic, pH 13), the Ecorr values of all three mixes moved towards the lower negative value of Ecorr, indicating better resistance to corrosion. Exposure time also has its influence on the corrosion potential. Longer the exposure period, more will be the negative value of Ecorr and more will be the corrosion rate.

In case of samples exposed to strong acidic marine environment (pH 1), the acid attack deteriorates the concrete at a much faster rate and hence there is a rapid ingress of chloride ions resulting in higher corrosion potential and similar phenomenon has been reported by [28]. After 90 days of exposure, PSC concrete mixes proved to be better corrosion resistant as a change in Ecorr values were significantly lesser than OPC and PPC concrete mixes. After 90 days of exposure, OPC concrete mixes had 10.3% more Ecorr value and PPC samples showed an increment of 6.6% in Ecorr value compared to PSC samples. This signifies PSC and PPC samples were more resistant to ingress of aggressive ions even with an increased duration of exposure, which can be attributed to the advancement of pozzolanic reaction. It can be observed from Figure 6 that for 30 days of exposure all three mixes showed almost similar corrosion rates. However, at 90 days of exposure, OPC and PPC samples show 1.92 and 1.29 times the corrosion rate than PSC samples.

As the acidity of the marine environment changed from pH 1 to pH 4, most of the samples exposed to mild acidic marine environment (pH 4) had a slightly lower value of corrosion potential compared to strong acidic exposure (pH 4). The corrosion rate of all the mixes reduced as the acidity changed from pH 1 to pH 4. PSC concrete mixes again showed lower corrosion rate compared to OPC and PPC concrete mixes. Samples exposed to a marine environment with pH 7 showed lesser negative corrosion potential than acidic marine environment (pH 1 and 4). This indicates that as the solution becomes more alkaline, the corrosion potential decreases. For 30 days of immersion, PSC concrete mixes showed lesser corrosion potential out of all three mixes whereas OPC concrete mixes showed slightly lower Ecorr value compared to PPC samples. After 90 days of immersion, PSC samples had lesser negative Ecorr value compared to OPC and PPC and an increment of 6.9% for OPC and 9.5% for PPC were noted compared to PSC samples. Similarly, analysis of corrosion rate shown the same scenario, PSC concrete mixes showed far better resistance to corrosion than OPC and PPC concrete mixes.

Samples exposed to a marine environment with alkaline exposure (pH 10 and 13) showed comparably lesser negative corrosion potential because of high alkalinity. This can be attributed to the fact that migration of chloride ions was hindered by the high alkaline nature of pH 10 and pH 13, which resulted in lower negative corrosion potential of all three mixes than the acidic marine exposure (pH 1 and 4). In this combination also PSC concrete mixes proved to be better resistant to corrosion potential than PPC and OPC mixes. It is interesting to note that OPC concrete mixes showed lesser corrosion potential than PPC concrete mixes at the early stage of exposure (30 days) which might be due to the attainment of high early strength. However, as the exposure period reached 90 days, OPC concrete had the higher corrosion potential than PPC and PSC concrete mixes. The corrosion rate of PSC concrete mixes was lesser compared to OPC and PPC concrete mixes for both the exposure periods.

Bond strength retention of OPC, PPC and PSC concrete mixes exposed to acidic and alkaline marine environment

The bond strength retention values for OPC, PPC and PSC concrete mixes for 30 and 90 days of exposure are presented in Figure 7. For all immersion periods, maximum loss of ultimate bond strengths was observed for concrete exposed to the strong acidic marine environment (pH 1) which could be due to the severe deterioration of concrete because of acid attack and higher corrosion of reinforcement bars. This indicates that pH of the solution deteriorates the concrete which reduces the compressive strength and also reduces bond strength between steel and concrete. During early exposure period OPC concrete had shown better bond strength retention compared to PPC and PSC concrete mixes except for acidic marine environment (pH 1). However, as exposure period increased to 90 days in acidic marine environment the bond strength retention of only 74% was observed for OPC mixes where as for PSC the bond strength retention was 90.2% was noticed. PPC falls in between with bond strength retention of 86%.

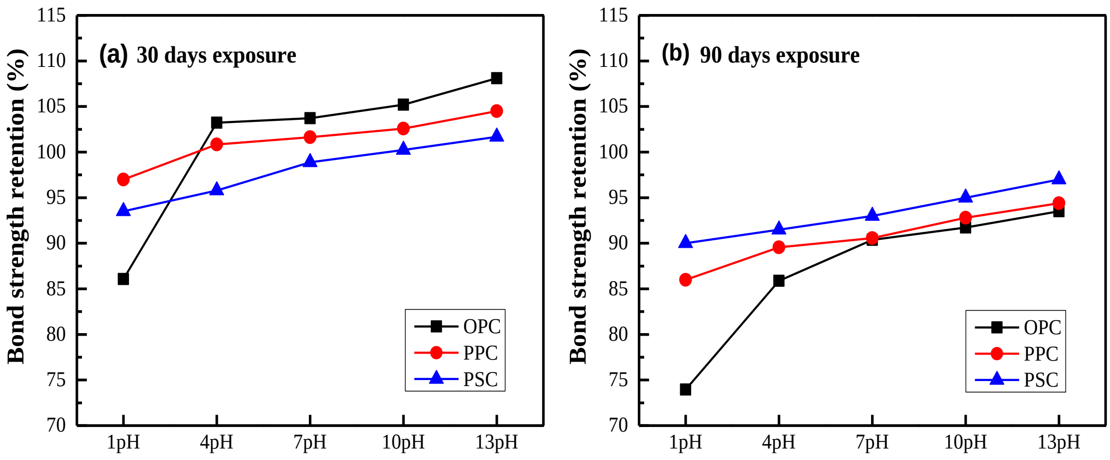

Figure 7 Bond strength retention after exposure to acidic (pH 1 and pH 4) and alkaline (pH 10 and pH 13) marine environment for different durations.

It is found that OPC concrete mixes showed relatively higher bond strength retention compared to PPC and PSC concrete mixes after 30 days of exposure. It can be observed that there was a slight increase in ultimate bond strength for the pH values more than four. Because of the aggressive environment there was a possibility of active corrosion in all the concrete mixes as corrosion product starts to accumulate along the periphery of the steel bar. Corrosion products will increase the friction between the reinforcing steel and surrounding concrete which resulted in increase of ultimate bond strength compared to the controlled one. However, as the exposure period increased, there was degradation of concrete which reduced the strength of concrete and increased diffusion of harmful ions (Cl^- and H^+) which might have accelerated the corrosion process and the corrosion products start to exert expansive pressure. It is to be noted that if the expansive pressure goes greater than the tensile strength of concrete, the initiation of corrosion cracks takes place which results in reduction of bond strength [31]. The bond strength retention of PSC samples was remarkable at an exposure period of 90 days in the aggressive marine environment.

The Relationship between Compressive Strength and Ultimate Bond Strength

The relationship between the ultimate bond strength (τ) and compressive strength (f_{ck}) of OPC, PPC, and PSC concrete samples are presented in Figure 8. A total of twenty points for each type of concrete was considered for the regression analysis. It can be observed that there is a meaningful relationship between the compressive strength and ultimate bond strength for all three concrete mixes. As the compressive strength increased, ultimate bond strength also increased significantly for OPC, PPC and PSC concrete mixes. It can be noted from the regression analysis that there is a linear trend fitting very well with 'R^2' values of 0.9028, 0.9383 and 0.9428 for OPC, PPC and PSC concrete respectively. The linear equations obtained by regression analysis for OPC, PPC, and PSC concretes are given by Equation 1, 2, and 3 respectively.

$$\tau = 0.383 (f_{ck}) - 3.5905 \quad (1)$$

$$\tau = 0.3324 (f_{ck}) - 1.1242 \quad (2)$$

$$\tau = 0.3408 (f_{ck}) - 1.7152 \quad (3)$$

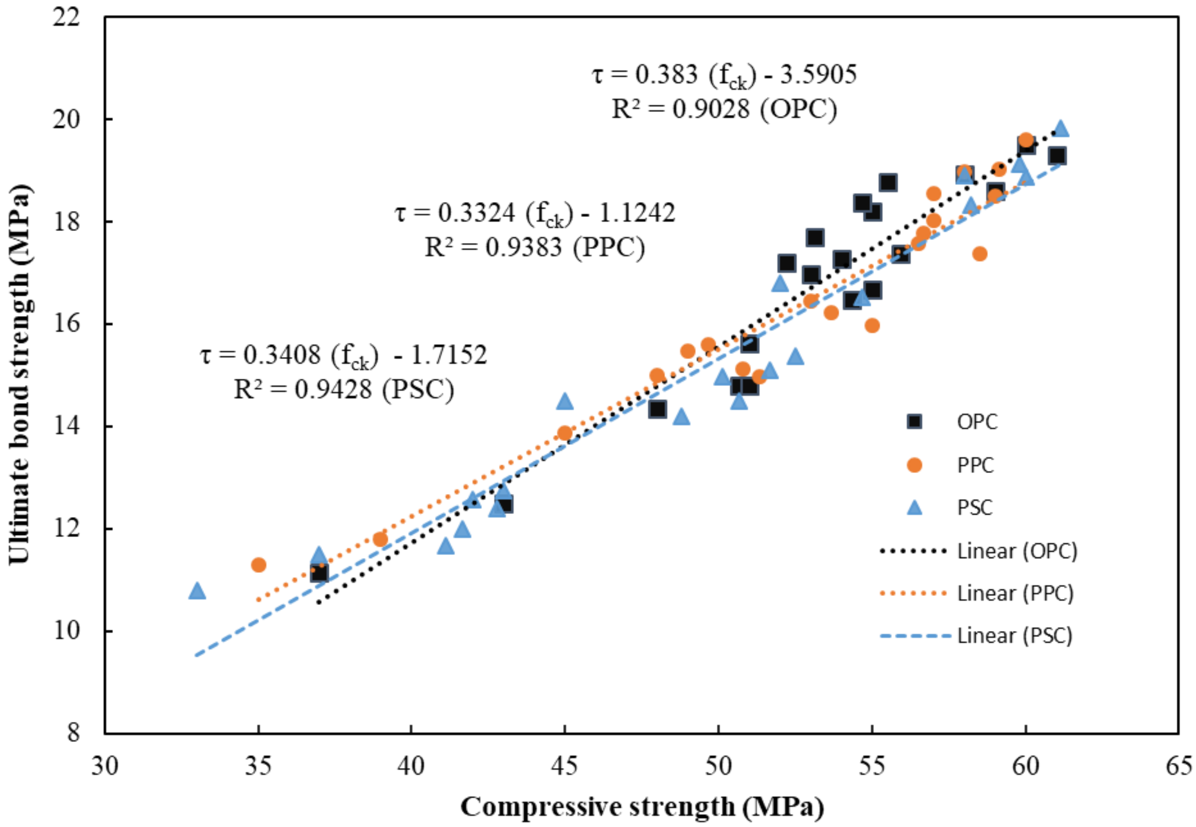

Figure 8 Relationship of bond strength and compressive strength of OPC, PPC and PSC concretes

CONCLUSIONS

The following conclusions were drawn from the present investigation.

- There was found to be a meaningful relationship between compressive strength and ultimate bond strength of OPC, PPC, and PSC concrete. As the compressive strength increased, ultimate bond strength too increased.
- The long-term curing, especially for PPC and PSC concretes helped in the advancement of pozzolanic reaction which might be the reason for enhanced bond strength compared to OPC concrete.
- Corrosion rates were found to be the lowest in PSC concrete samples. Compressive strength retention and bond strength retention of PSC concrete was found to be better than PPC and OPC concretes.
- The acidic marine environment was more detrimental compared to alkaline marine exposure.
- The performance of PSC concrete was better in acidic as well as alkaline marine environment compared to PPC and OPC concrete.

- OPC concrete mix is vulnerable to alkaline marine environment, whereas, PPC and PSC concrete mixes are not susceptible to alkaline marine environment.

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