Construction and Building Materials 154 (2017) 349–360

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Long-term corrosion performance of blended cement concrete in the marine environment – A real-time study

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HIGHLIGHTS

- Long-term and real-time corrosion performance of blended cements namely PPC and PSC was carried out and compared with OPC.
- The concrete samples were exposed to atmospheric, splash and immersion zone.
- The concrete cubes were exposed over the period of 10 years.
- Compressive strength, alkalinity, free chloride content and sulphate content, bio-fouling attachment and electrochemical properties were carried out.
- The studies revealed that the blended cement concretes are having higher corrosion resistance in all three exposure zones than that of OPC concrete.

ARTICLE INFO

Article history:
Received 11 April 2017
Received in revised form 14 July 2017
Accepted 31 July 2017
Available online 5 August 2017

Keywords:
Blended cements
Concrete
Corrosion
Marine environment
Concrete exposure
Chloride
Sulphate

ABSTRACT

Blended cement is widely used in critical structures mainly because of its enhanced corrosion resistance concerning its durability. This paper presents the long term corrosion performance of blended cements namely; Portland pozzolana cement (PPC) and Portland slag cement (PSC) concrete under the three marine exposure conditions such as, atmospheric zone (AZ), immersion zone (IZ) and splash zone (SZ). Offshore Platform Marine Electrochemistry Center (OPMEC), Tuticorin, Tamil Nadu, India was selected as an exposure station. The concrete cubes were exposed over the period of 10 years and their physico-chemical properties such as compressive strength, alkalinity, free chloride content and sulphate content, bio-fouling attachment and electrochemical properties like, AC-impedance and potentiodynamic polarization were carried out and the results obtained were compared with Ordinary Portland Cement (OPC) concrete. XRD and SEM studies were also carried out for both OPC, PPC and PSC concrete samples exposed under various zones. It was observed that the strength and alkalinity of the blended cement concretes were relatively equal to that of OPC concrete. In addition, the pH values of the blended cement concretes are above the threshold limit recommended for depassivation. Furthermore, the resistance to chloride ion penetration was significantly reduced for blended cement concretes than that of OPC concrete and also exhibited very high amount of bio-fouling attachment. The electrochemical studies revealed that the blended cement concretes are having higher corrosion resistance in all three exposure zones than that of OPC concrete. From the results it is observed that the blended cement concretes are technically viable from the durability point of view and highly recommended for aggressive marine environments rather than OPC concrete.

1. Introduction

Reinforced concrete has become a fundamental component in the modern construction industry and it has an excellent structural properties. However, its early deterioration in the marine environment, severely affecting the lifespan of the structures and involving financial impact on rehabilitation cost [1]. The deterioration of concrete in the marine environment is mainly due to the chloride-induced reinforcement corrosion. The penetration of the chloride ions from the marine environment caused depassivation of reinforcement and consequently damage the concrete. The development of newer concrete materials that are highly resistant

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.237

to the ingress of chloride ions has become imperative, and it can be possible only by reducing the permeability of the concrete [2]. Over the past decades, many researchers have achieved the low permeability concrete using supplementary cementitious materials including silica fume, fly ash, blast furnace slag, activated metakaolin, rice husk ash etc., [3–5]. The pozzolanic reaction of the supplementary cementitious materials significantly reduced the permeability of the concrete in hardened states. However, as mentioned above the supplementary cementitious materials, slag and fly ash (FA) has been widely used as a successful replacement materials for Ordinary Portland Cement (OPC) [6–8]. The test results of Lane and Best [9] demonstrated that the strength of the fly ash blended cement concrete was 20% higher than ordinary Portland cement concrete. Puertas et al., [10] studied the effect of strength development and hydration of alkali-activated slag/fly ash blended cement concrete, and it was found that blended cement reduced the alkali-silica reaction (ASR) and sulphate damage of the concrete than that of OPC. Khatri et al. [11] reported that the coefficient of water permeability values of the slag blended cement concrete was very much lesser than OPC. A long term corrosion study on blended cement concrete relating to fly ash replacement level demonstrated that the chloride penetration, chloride diffusion coefficient and steel corrosion in concrete reduced with the increase in the fly ash substitution rate [2,12,13]. Cheewaket et al. [2] found that the chloride binding capacity of the fly ash concrete decreased significantly within 4 years of marine exposure, after that its value was almost constant. Most of the studies carried out so far, concentrated on the durability properties of the concrete made with supplementary cementitious materials replaced blended cement under laboratory exposure conditions, accelerated test and simulated environmental conditions [14–18].

In view of the above, this study focused on investigating the long-term corrosion performance of factory made blended cements under real-time marine exposure conditions such as, atmospheric, immersion and splash zone conditions over a period of 10 years. Two types of blended cement namely, Portland pozzolana cement (PPC) and Portland slag cement (PSC) was used in this study and their durability performances were compared with OPC under three exposure field conditions namely, atmospheric zone (AZ), immersion zone (IZ) and splash zone (SZ).

2. Experimental investigation

2.1. Materials

2.1.1. Cement

Three types of cement namely Ordinary Portland Cement (OPC), Portland Pozzolona Cement (PPC), Portland slag cement (PSC) confirming to IS:8112-1989 [19], IS:1489-Part-I:1991 [20], IS:455 [21], respectively are used for this study. The chemical analysis was obtained from the cement manufacturer for all types of cements and the nominal chemical composition is given in Table 1. The specific gravity of the OPC cement used was 3.14.

Table 1
Chemical composition of OPC, PPC and PSC.

Compound	Weight (%)		
	OPC	PPC	PSC
Silicon-di-oxide (SiO_2)	20–21	28–32	26–30
Aluminium oxide (Al_2O_3)	5.2–5.6	5.0–8.0	9.0–11.0
Ferric oxide (Fe_2O_3)	4.4–4.8	4.9–6.0	2.5–3.0
Calcium oxide (CaO)	62–63	41–43	44–46
Magnesium oxide (MgO)	0.5–0.7	1.0–2.0	3.5–4.0
Sulphur-tri-oxide (SO_3)	2.4–2.8	2.5–2.8	2.8–2.9
Loss on ignition (LOI)	1.5–2.5	3.0–3.5	1.5–2.5

2.1.2. Fine and coarse aggregates

The natural river sand passing through 4.75 mm sieve was used as a fine aggregates and the blue metal jelly having an average size of 20 mm was used as a coarse aggregates. The specific gravity of the fine and the coarse aggregates was tested as per IS 2386(3):1963 [22], and the value was found to be 2.48 and 2.67, respectively. Sieve analysis was carried out on both fine and coarse aggregates, according to IS 2386(1):1963 [23] and the fineness modulus of fine aggregates and coarse aggregates used was 2.75 and 7.25 respectively.

2.1.3. Concrete

According to the procedure described in IS 10262 [24], the concrete mix proportions were designed to achieve the target strength of 30 N/mm^2 and the mix proportion was 1: 1.80: 3.696. A constant water cement ratio (W/C) of 0.55 was followed for all the three types of cements. The detailed formulation of concrete mix proportions used is listed in Table 2.

2.2. Concrete specimen preparation

The concrete specimens were prepared for all three types of cements such as OPC, PPC and PSC. For all three concretes, aggregates such as cement, natural sand and coarse aggregates were weighed in a dry condition and then mixed together in a laboratory counter current mixer, in order to avoid aggregate and water loss. Using slump cone test the workability of the concrete was measured. In order to measure the physicochemical properties of concrete, the concrete cubes of size 150 × 150 × 150 mm was cast for all three cements. For electrochemical studies, the same size of 150 × 150 × 150 mm cubes were prepared with 12 mm dia. Thermo Mechanically Treated (TMT) rebar having a length of 70 mm. Each cube specimen contains two rebars embedded parallelly just opposite to each other in the cube at a cover of 40 mm as shown in Fig. 1. All cube samples were filled with concrete in three layers, and each layer of the concrete was adequately compacted using a table vibrator. After casting, all the specimens were covered with a plastic sheet to avoid moisture loss and the specimens were kept at a room temperature for 24 h. after that were demoulded and immersed in water for curing under the temperature of 23 ± 2 °C for 28 days.

2.3. Specimen exposure and exposure station

After required curing, the concrete cubes were exposed to three field exposure conditions such as atmospheric zone (AZ), immersion zone (IZ) and splash zone (SZ). Offshore Platform Marine Electrochemistry Center (OPMEC), Tuticorin, Tamil Nadu, India was selected as an exposure station. The exposure station is located in Tuticorin new harbor area on the southeast coast of India, established in the year of 1987 by CSIR-CECRI, India. It is constructed in the open sea, and a water depth was about 5 m. This center is having an superior facility and this facility offers an excellent environment for investigating marine corrosion under the tropical marine Indian climatic conditions and the bio-fouling phenomenon round-the-year. The ambient temperature of the atmospheric zone (AZ) was ranging from 25 °C to 35 °C. In the immersion zone (IZ), the concrete cubes were immersed in the sea at a depth of 5 m. The pH value of the sea water at the place of IZ was ranging from 7.9 to 8.2 and the chloride and sulphate concentrations was ranging from 2200 to 2600 ppm. In the splash zone (SZ) the cubes were subjected to natural wave alternate wetting and drying conditions. The wetting of cubes was achieved by sea water having a chloride and sulphate concentrations ranging from 16,000 to 18,000 ppm and the drying achieved in atmospheric with the temperature ranging from 25 °C to 35 °C. Corrosion measurements were carried out periodically on the steel rebar embedded in the cubes, over the period of 10 years. The photographic image of the exposed site specimens at AZ, SZ and IZ exposures were shown in Fig. 2.

2.4. Testing methods

2.4.1. Physicochemical properties of concrete

2.4.1.1. Compressive strength. The compressive strength of concrete was carried out as per IS:516-1959 (R1999) [25]. Concrete cube specimens of 150 × 150 × 150 mm were cast with different types of blended cement concrete. After 24 h, the specimens were demoulded and immersed in water for curing. After 28 days of curing, the concrete cubes were exposed to various zones of marine environment over a period of 10 years. Then the exposed concrete specimens were tested on the compression testing machine of 2000 kN capacity at a rate of loading of 140 kN/min. The ultimate load at failure of the cube was noted and the compressive strength was calculated.

2.4.1.2. pH measurement. The pH of the extracts derived from the OPC, PPC, and PSC concrete cubes was measured initially and after 10 years of exposure. Core samples collected from various concrete were powdered and then passed through the sieve of 150 µm. Then 20 g of powder was added to 60 ml of distilled water. The mixture was shaken well using microid mechanical shaker for 1 h. and the solution was filtered through a Whatmann filter paper. The pH of the filtrate was measured using a