Construction and Building Materials 187 (2018) 426–438

Contents lists available at ScienceDirect

Construction and Building Materials

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

Behavior of high performance concrete pastes with different mineral admixtures in simulated seawater environment

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HIGHLIGHTS

- The influence of different mineral admixtures on resistance to simulated seawater was investigated.
- The addition of mineral admixtures except of LP can inhibit the expansion of the pastes after 180 d.
- FA paste has a good effect on resistance to simulated seawater.
- The microstructure of the pastes with mineral admixtures is denser than that of the pure cement paste in simulated seawater.

ARTICLE INFO

Article history:
Received 5 February 2018
Received in revised form 4 July 2018
Accepted 25 July 2018

Keywords:
High performance concrete
Paste
Marine environment
Mineral admixture
Durability

ABSTRACT

With the blooming of ocean construction engineering, the influence of seawater on concrete durability draws increasing attentions. This paper investigates the performances of five high performance concrete (HPC) pastes, including pure cement paste, fly ash (FA) paste, limestone powder (LP) paste, ground granulated blast-furnace slag (GGBS) paste and silica fume (SF) paste, soaked in simulated seawater. The results indicate that the addition of FA would improve the strength of paste soaked in simulated seawater compared to pure cement paste from 90 d to 360 d and the order of strength in 360 d was, FA paste > Pure cement paste > LP paste > GGBS paste > SF paste. All mineral admixtures except LP can inhibit the expansion of paste soaked in simulated seawater at later age and the order of expansion rate in 360 d was, LP paste > Pure cement paste > FA paste > GGBS paste > SF paste. The internal structure of pastes soaked in simulated seawater at 360 d mainly contains $Ca(OH)_2$, AFt, gypsum, $Mg(OH)_2$, C_3S and C_2S while the external structure of pastes mainly contains $Mg(OH)_2$, $CaCO_3$ and AFt through the XRD spectra. SEM results proved that the addition of mineral admixtures can make the structure of the pastes denser.

1. Introduction

Ocean construction concrete structure has to serve in a very harsh environment for a long life span. Many facts and engineering practice [1,2] have shown that concrete structure in ocean construction engineering has been severely eroded before its designed service life due to various reasons, some of them must be repaired in less than 20 years, and some even need to be rebuilt within 5 years [3]. Concrete structure in marine environment is subjected to physical damage and chemical erosion, especially those in surge area and splash zone [4]. The principle of physical damage are relatively simple, for example, it would be caused by alternating wet and dry, temperature gradient and long-term abrasion by sea waves and sand [5]. The chemical erosion usually occurs in the erosion medium, and the erosion medium consists of four types: fresh water, acid, alkali, and salt. The chemical erosion mainly included [6] dissoluble erosion, soluble erosion and expansive erosion. Concrete resistance to seawater erosion determines the serviceability of concrete in marine environment. However, a great deal of facts [7–11] have proved that ordinary concrete cannot meet the requirement of durability in marine environment, therefore, how to increase the resistance of concrete on seawater and consequently extend the service life of concrete becomes an important issue drawing extensive attention.

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https://doi.org/10.1016/j.conbuildmat.2018.07.196
0950-0618/

High performance concrete (HPC), a kind of concrete with mineral admixtures, has high amounts of cementitious material and low water cement ratio [12]. It has been widely used in ocean construction engineering for its stronger resistance to all kinds of deleterious ions than ordinary concrete [13–15]. The addition of an appropriate amount of mineral admixture can refine and improve the pore size distribution of the hardened cement paste [16], reduce the number of large pores, increase the number of small and connected ones and mineral admixture can fill into the pores of the aggregate and cement particles in varying degrees which can improve the density of concrete and ultimately achieve the purpose of improving the performance of the concrete [17]. At present, many researchers [18–20] adopt indoor simulation environment accelerated method to study the behavior of HPC paste. Field sampling detection can be a more realistic method to study the influence of seawater on concrete. Field samples were taken at the typical parts of the concrete that were eroded and had less stress. A field sample can only get the result of a certain time, a certain point of detection. However, erosion is a process of slow and dynamic change, which requires multiple sampling tests. This way will inevitably affect the durability of concrete.

Many studies have confirmed that mineral admixtures can improve the durability of concrete. W. Chalee demonstrated that the increase of FA replacement in concrete obviously weaken the chloride penetration and steel corrosion in concrete [21]. Hu Shuguang has proved that the addition of large amount of slag with low Al content is beneficial to improve the sulfate resistance of concrete, but with the increase of slag content, the early strength of concrete become lower [22]. Wiegrink confirmed that the creep of concrete after adding 10 wt% SF is smaller than that of concrete without SF [23]. Islam has verified that the concrete with 30 wt% slag has best effect on resistance to seawater [24]. Both Sotiriadis [25] and Deng Dehua [26] proved that the addition of limestone powder will cause large volume expansion and cracking of cement paste in the sulfate environment and result in a large drop in strength. On the opposite, Zelic has experimentally proved that the addition of limestone powder will enhance the ability of concrete to resist the erosion of sulfate [27].

Mostly, current researchers [28–31] use the single factor simulation method to study the effect of deleterious ions on concrete, ignoring the interaction among the deleterious ions in seawater. In this paper, HPC pastes with different mineral admixtures were prepared, the cement paste compressive strength, volume expansion, the XRD and SEM have been studied and the effect of different mineral admixtures on resistance to erosion of simulated seawater and the erosion effect of different ions were discussed, this investigation contributes to understanding the behavior of the HPC in marine environment.

2. Experiment

2.1. Materials

The chemical compositions of cement, ground granulated blast-furnace slag (GGBS), silica fume (SF), fly ash (FA) and limestone powder (LP) used in this paper are shown in Table 1. The water reducing agent is polycarboxylate superplasticizer, produced by ShangHai MaBei Building Materials Co Ltd, the water reduction rate is about 30%. The water is tap water of Wuhan City, all of them are commercially available.

2.2. Simulated seawater

To investigate the interaction of various deleterious ions on the HPC paste, the simulated seawater with 1.9 wt% NaCl, 0.15 wt% $NaSO_4$ and 0.13 wt% $MgSO_4$ was prepared according to the composition of the seawater [32] and the composition of the seawater and simulated seawater is shown in Table 2. In this paper, the fresh water, which may cause a strength decrease in the long-term, was used as contrast.

2.3. Experiment procedure and methods

1) The FA, LP, SF and GGBS were dried at 60 °C for 24 h. The GGBS and LP were grinded by a 500 mm diameter and 500 mm height standard ball mill for 30 min and then passed through a 0.075 mm sieve. Then the cement, GGBS, FA, LP and SF were mixed evenly in the ball mill according to the set ratio. The simulated seawater and fresh water were put in a constant temperature of 20 °C and replaced every 30 d. The samples were taken into the solutions after standard curing for 1 day. The types and quantities of mineral admixtures in concrete paste both affect the performance of the concrete. This paper chooses the optimal mineral admixture ratio shown in Table 3 based on many scholars' studies [33–35] and the weight of HPC pastes of all sets per cubic meter in kg are shown in Table 4. The amount of water-reducing agent is 1.6 wt% by weight of binder and the water-binder ratio is 0.2.
2) The measurement for compressive strength of HPC paste was carried out following the Test Method for Strength of Cement Paste of GB/T17671-1999 [36]. The dimension of prism specimens for strength measurement is $40 \times 40 \times 40\ mm^3$. The compressive strength of 3 days, 7 days, 28 days, 90 days, 180 days and 360 days were measured. The strength loss rate (K_s) of the pastes is calculated according to the formula (1).

$$K_s = \frac{P_i - K_i}{P_i} \tag{1}$$

Table 1
The chemical compositions of cementitious materials (wt%).

Oxide (%)	Cement	GGBS	SF	FA	LP
CaO	59.75	38.14	0.54	3.71	53.76
MgO	3.17	9.14	0.91	0.61	0.46
Al_2O_3	6.83	15.50	0.27	33.01	0.44
SiO_2	21.47	32.69	94.48	47.22	2.43
TiO_2	–	0.7	–	1.61	–
SO_3	1.06	1.73	–	1.44	–
Fe_2O_3	5.6	1.70	0.87	4.14	0.28
Loss	1.26	–	–	–	–
Amount retained on 80 um sieve (%)	8.6%	9.9%	–	7.6%	8.4%
Amount retained on 45 um sieve (%)	24.7%	30.5%	–	19.5%	28.8%

Note: Specific surface area (Blaine) of the silica fume is approximately 20000 m^2/kg.

Table 2
Composition of seawater and simulated seawater (wt%).

Composition	Na^+	Mg^+	Cl^-	Ca^{2+}	SO_4^{2-}	H_2O	Else
Seawater	1.08	0.13	1.94	0	0.27	94.48	0.1
Simulated seawater	2.05	0.13	1.9	0	0.28	95.64	–