Construction and Building Materials 63 (2014) 303–310

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effect of sodium hydroxide concentration on chloride penetration and steel corrosion of fly ash-based geopolymer concrete under marine site

P. Chindaprasirt [a], W. Chalee [b,*]

[a] Sustainable Infrastructure Research and Development Center, Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand
[b] Department of Civil Engineering, Faculty of Engineering, Burapha University, Chonburi 20131, Thailand

HIGHLIGHTS

- The long term durability of geopolymer concrete under marine site was investigated.
- The findings provide valuable data for a practice guide line of geopolymer concrete.
- The findings could help select for fly ash geopolymer concrete used in marine site.

ARTICLE INFO

Article history:
Received 6 August 2013
Received in revised form 27 February 2014
Accepted 1 April 2014

Keywords:
Marine environment
Fly ash-based geopolymer concretes
Chloride penetration
Steel corrosion
Sodium hydroxide concentration

ABSTRACT

In this research, the effect of sodium hydroxide (Na(OH)) concentrations on chloride penetration, steel corrosion and compressive strength of fly ash-based geopolymer concretes under marine environment were studied. The geopolymer concrete were prepared from class C fly ash with sodium silicate (Na_2SiO_3) and sodium hydroxide (Na(OH)) solutions. The concentrations of Na(OH) of 8, 10, 12, 14, 16 and 18 molar, and the constant molar ratio of SiO_2/Al_2O_3 were used. The $200 \times 200 \times 200$ mm^3 concrete cube specimens with steel bar embedded at coverings of 20, 50 and 75 mm were investigated. The specimens were air-cured in laboratory for 28 days and then were exposed to tidal zone of marine environment in the Gulf of Thailand. After 3-year exposure, the specimens were tested for compressive strength, chloride penetration and corrosion of embedded steel bar. The results showed that the chloride penetration and corrosion of embedded steel decreased with the increasing of Na(OH) concentration. The steel corrosion was related to the compressive strength of geopolymer concrete. The corrosion is high with the concrete of low compressive strength. In addition, increasing the Na(OH) concentration in geopolymer concrete resulted in a decrease in the chloride binding capacity.

1. Introduction

The high performances materials (low cost, high durability and high strength) needed to be achieved in the new construction. The new materials from industrial wastes are an interesting possibility for sustainability and economically use of resource. An industrial waste is generally used as pozzolanic materials to partially replace Portland cement for a high performance concrete (good mechanical and durability properties) [1–3]. However, they cannot totally replace Portland cement since silica (SiO_2) and alumina (Al_2O_3) in pozzolanic materials still need $Ca(OH)_2$ from hydration process for its pozzolanic reaction to produce calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) which is primarily responsible for the concrete strength [4]. Recently, it was found that pozzolanic materials containing SiO_2 and Al_2O_3 could be activated with alkaline solution at room temperature to produce a cementitious material called geopolymer [5]. Previous research had studied the effect of various factors such as alkalinity concentrations, curing condition and types of source materials on the microstructure and mechanical properties of geopolymer paste or mortar [6–10]. However, there are only a few reports concerning the durability properties of geopolymer concrete in real exposure which is significant for practical used, especially, the deterioration of geopolymer concrete caused by severe environment.

Current researches on geopolymer concrete are mainly focused on geopolymer properties such as mechanical properties, paste properties [6–10] and durability properties in laboratory [11–13]. However, no specific publications are available concerning the durability of geopolymer concrete in the actual marine site which is mainly due to sulfate attack and the corrosion of steel under chloride attack [14,15]. However, all of these mechanisms are the

* Corresponding author. Tel.: +66 8 97915171.
E-mail address: wichian@buu.ac.th (W. Chalee).

http://dx.doi.org/10.1016/j.conbuildmat.2014.04.010
0950-0618/

combination of many influences, such as moisture, temperature, impact force and abrasion by sand in sea water. The combined destruction of chemical and physical aggressive of actual environment are complicated. Consequently, the long term durability study in marine site was needed for the development of good practice guide line on selection and design for fly ash geopolymer concrete in marine environment. Thus, the goal of the study was to study the fly ash-based geopolymer concrete under the marine environment in order to achieve the good mechanical and durability properties for marine structure. The effect of sodium hydroxide (NaOH) concentrations on compressive strength, chloride penetration profile, chloride binding capacity and steel corrosion of fly ash-based geopolymer concretes under 3-year exposure in tidal zone of marine environment were carried out.

2. Experimental program

2.1. Materials and specimens

The geopolymer concrete mixtures were prepared from Mae Moh class C fly ash with a 30-μm median particle size (by sieve analysis), sodium silicate (Na_2SiO_3, NS) solution with 9% Na_2O and 30% SiO_2 by weight, NaOH solution, graded sand, and crushed limestone with a maximum size of 19 mm. The chemical compositions of fly ash are shown in Table 1. The NaOH concentrations were varied at 8, 10, 12, 14, 16 and 18 molar and the molar ratio of SiO_2/Al_2O_3 was kept constant. The liquid to binder ratio (L/B) was kept constant of 0.60. Mixture proportions of fly ash-based geopolymer concrete are shown in Table 2. For the mixture procedure, the fly ash and aggregates were dry-mixed with a power mixer, the alkaline liquids (NaOH and sodium silicate solutions) were sequentially added and the wet-mixing was continued for 1 min. These were similar to the mixing of normal concrete. Concrete cylinder having 100-mm in diameter and 200-mm in height were prepared for compressive strength test. For chloride penetration and steel corrosion tests, the $200 \times 200 \times 200\ mm^3$ geopolymer concrete cube specimens were cast and the steel bars (12-mm in diameter and 50-mm in length) were embedded at the corners of concrete specimens with the covering depths of 20, 50, and 75 mm. The embedded steel bars which is commonly used for reinforced concrete construction were cut from 12-mm diameter round bar graded SR24 (yield strength of 240 MPa). Geopolymer concrete specimens preparations are shown in Fig. 1(a). The geopolymer concrete specimens were removed from the molds at the age of 1 day and then were air cured until the age of 28 days. Consequently, the geopolymer concrete specimens were transferred to the tidal zone of the marine site in the Gulf of Thailand as shown in Fig. 1(b). The ranges of annual temperature at this site are between 26 and 35 °C, and based on chemical analysis of the seawater, chloride and sulfate compositions range from 16,000 to 18,000 and 2200 to 2600 mg/l, respectively. The geopolymer concrete specimens were exposed to two wet–dry cycles of seawater daily.

2.2. Tested program

2.2.1. Compressive strength

The compressive strengths of geopolymer concretes at 28 days and at 3 years exposure in marine environment were investigated in accordance with ASTM C39/39M [16]. The compressive strength was collected based on the average of values obtained from three samples.

2.2.2. Chloride penetration

After being exposed to seawater for 3 years, the top surface of concrete cube specimens were cored to obtain 75-mm diameter cylinders. The core specimens were dry-cut from the surface to obtain a series of 10-mm thick slices, and then were ground into small powdery particles. The powder sample from each slice was selected for chloride tests by acid-soluble and water-soluble to determine the total and free chloride contents in geopolymer concrete, respectively. The acid-soluble and water-soluble chloride tests were conformed to ASTM C 1152 [17] and ASTM C1218 [18], respectively. The specimens preparation for chloride penetration test are shown in Fig. 2(a).

Table 1
Chemical composition of fly ash.

Chemical composition (%)	
Silicon dioxide, SiO_2	32.10
Aluminum oxide, Al_2O_3	19.90
Iron oxide, Fe_2O_3	16.91
Calcium oxide, CaO	18.75
Magnesium oxide, MgO	3.47
Sodium oxide, Na_2O_3	0.69
Potassium oxide, K_2O	2.38
Sulfur trioxide, SO_3	2.24
Loss on ignition, LOI	0.07

Table 2
Mixture proportions of fly ash-based geopolymer concrete.

Mix	Mixture proportion (kg/m^3)				
	Fly ash	Fine aggregate	Coarse aggregate	NaOH	NS
8-M	390	585	1092	67	167
10-M	390	585	1092	67	167
12-M	390	585	1092	67	167
14-M	390	585	1092	67	167
16-M	390	585	1092	67	167
18-M	390	585	1092	67	167

2.2.3. Steel corrosion and chloride content at the position of embedded steel

The embedded steel corrosions were measured in terms both of the percentage of rusted area (RA) and percentage of weight loss (WL). After 3-year exposure in marine site, the geopolymer concrete specimens were broken, and then the embedded steel bars were removed. An image of each visible surface of rusted steel was recorded. For the percentage of rusted area, transparent paper with a grid composed of 1 mm-squares was then wrapped around each embedded steel bar. The visible surface of the rusted steel was marked on the paper and evaluated (Fig. 2(b)). The corrosion of the embedded steel bars was measured in terms of the percentage of rusted area by comparing the surface rusted area to the total surface area of the embedded steel. Also, the percentage of weight loss of embedded steel bar were determined by comparing the amount of steel weight loss due to corrosion (the decrease in embedded steel weight during the exposed time period) to the initial steel weight (the steel weight before embedding in geopolymer concrete). In addition, mortar debris was collected from the position of the embedded steel–concrete matrix interface and ground to powder. Its water-soluble chloride content was determined and represented the free chloride content at the position of the embedded steel.

3. Results and discussions

3.1. Compressive strength

Table 3 shows the compressive strength results for fly ash-based geopolymer concretes after 28-day curing in air and 3 years exposure in the tidal zone of marine site. Also shown is the strength at 3 years as a proportion of the 28-day strength in order to present the degree of strength loss or strength gain. The 28-day compressive strength of geopolymer concretes increases with the increase in NaOH concentration. All geopolymer concretes recorded no strength loss between 28 days and 3 years, especially in geopolymer concrete with high strength grade. The increasing compressive strength of geopolymer concrete between 28 days and 3 years tended to be high with the increase of Na(OH) concentration and the highest increase was in geopolymer concrete with sodium hydroxide concentration of 18 molar. For instance, geopolymer concrete with Na(OH) concentration of 8, 10, 12, 14, 16 and 18 molar had percentage compressive strength at 3 years as compared to 28 days of 107.3%, 112.8%, 117.7%, 125.2%, 125.2% and 126.1%, respectively. During exposure period, the compressive strength gain of geopolymer concrete with higher strength grade (higher NaOH concentration) was larger than the lower strength grade (lower NaOH concentration). The high concentration of NaOH resulted in the leaching of a larger amount of Si and Al from fly ash [8] and thus produced a better degree of polycondensation and resulted in a high development of long-term compressive strength of geopolymer concrete [19–21]. However, some previous research [9] found that the leaching of Si and Al from fly ash tend to decrease at a high concentration of Na(OH). This may be caused by an increase in the viscosity and density of NaOH solution result in a high viscosity and low flow ability. Consequently, lower pore surface-solution interaction is expected. This trend was consistent