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Review

Durability of concrete structures in tropical atoll environment

Hongfa Yu[a,*], Bo Da[a], Haiyan Ma[a], Haiwei Zhu[a], Qiang Yu[b], Haimin Ye[c], Xianshuang Jing[c]

[a] Department of Civil Engineering, Nanjing University of Aeronautics and Astronautics, 210016 Nanjing, China
[b] Navy Research Center of Coastal Defense Engineering, 100070 Beijing, China
[c] Engineer, The People's Liberation Army Unit 92003, 524003 Zhanjiang, China

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ABSTRACT

A literature investigation and field surveys were made to explore the durability to destruction of Ordinary Portland cement Concrete (OPC) and Coral Aggregate Concrete (CAC) structures in a tropical atoll environment. The surface free Cl^- concentrations (C_s) and apparent chloride diffusion coefficients (D_a) were calculated and the calculation method of D_a in a one-dimensional half-infinite-body concrete structure was explored. The results show that the complex and severe environment of tropical atolls corrodes concrete structures badly and that the reinforcement corrosion rate is high. For a concrete structure in a tropical atoll, C_s of OPC is generally smaller than that of CAC. At the same time, the D_a of concrete calculated by the least squares method is the most reliable according to Fick's second law of diffusion. The calculated results demonstrate that the value of D_a is generally smaller in OPC than in CAC. Smaller water-to-binder ratios and higher strengths cause decreases in D_a for CAC. When OPC is not available in tropical atoll projects, the water-to-binder ratio should be decreased and the strength should be enhanced in CAC, which should improve the durability of the concrete effectively and decrease the C_s and D_a of the concrete structure.

1. Introduction

In the tropical marine environment, concrete structures suffer premature failure from Cl- erosion, carbonization, and the wash and wear of waves, seriously impairing the security and durability of tropical marine engineering structures (Pack et al., 2010; Aveldaño and Ortega, 2010). At present, studies on the durability of concrete mainly focus on the north of the equator, the tropical/subtropical concrete durability researches are relatively few, and the chloride diffusion studies are even fewer. In the coral concrete, the reinforcement is easier to be corroded for its defect-many natural pores and plentiful chlorides. It is very important to investigate the durability of ordinary Portland cement concrete (OPC) and coral aggregate concrete (CAC) structures.

During the Second World War, both America and Japan (Nutter, 1943; Rasmussen, 1946; Perry, 1945; Rick, 1991; Narver, 1954; Engineering Study, 1960; Scholer, 1959) used CAC extensively to build airports, roads, and architecture in Pacific atolls, including the Hawaiian, Midway, Gilbert, and Marshall Islands, the Kwajalein Atolls, Bikini Atolls, Eniwetok, Johnston, Wake, Mariana (Saipan and Guam), Samoa, Solomon Islands, and Miyakojima. In the 1950s and 1960s Scholer (Scholer, 1959) began research on the durability of CAC structures. In 1974, Howdyshell (Howdyshell, 1974) published an investigation on CAC, proposing that coarse coral aggregates could be used to make concrete. In 1982, Vines (Vines, 1982) found that the structural strength and durability were lower in CAC structures in South Pacific Samoa. In 1985, Ootani et al. Ootani et al. (1985) reported on the properties of CAC from Miyakojima. Since 1980, China has utilized OPC and CAC (Wang, 1988) in South China Sea atolls, gaining much engineering experience and providing good examples for the investigation of durability in related concrete structures. Past investigations of the durability of maritime concrete structures were mainly performed on OPC in the Bohai gulf, Eastern China, and Southern China, but the durability of OPC and CAC in the South China Sea was not studied.

Through literature and field investigations, the cracking, spalling, and corroding of reinforcements in tropical atolls were analysed. The corrosion rates, corroded reinforcement strengths, and Cl^- concentration depth distributions of concrete were tested throughout the systems. The surface free Cl^- concentration (C_s) and apparent Cl^- diffusion coefficient (D_a) in different concretes were researched using a modified version of Fick's second law of diffusion (Yu et al., 2002), providing data for researching the durability of concrete structures in tropical atolls.

* Corresponding author.
E-mail address: yuhongfa@nuaa.edu.cn (H. Yu).

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Table 1
Engineering information of concrete structures in tropical atolls.

No.	Concrete category	Research method	Maritime area	Research area	Experiment/photo age/years	W/B	28d f_{cu}/MPa	S/m
1	CAC	Literature research	Marshall Islands	Eneu, Bikini Atoll: Communication buildings (Rick, 1991)	11	~0.55–0.6	20.7*	92
2	CAC			Eneu, Bikini Atoll: Power house bunker (Rick, 1991)	16		24.9	92
3	CAC			Eneu, Bikini Atoll: Timing bunker (Rick, 1991)	16		24.6	92
4	CAC			Kwajalein: Breakwater (360 encyclopedi a)	3	–	–	0
5	CAC			Kwajalein: Building A (360 encyclopedi a)	3	–	–	–
6	CAC		Mariana Islands	Saipan: Building B (360 encyclopedi a)	76	–	–	–
7	CAC			Saipan: Building C (360 encyclopedi a)	76	–	–	–
8	OPC	Field research	Paracel Islands in the South China Sea	Abandoned garage	25	–	20.0 (Wang, 1988)	~90–100
9	OPC			Cement mortar of prefabricated steel mesh	40	–	–	15
10	OPC			Building D	22	–	–	~5–15
11	CAC			Lighthouse	25	0.54	27.5 (Wang, 1988)	0
12	CAC			Breakwater	19	0.63	20.9 (Wang, 1988)	~0–5

Note: 1). S is distance from the seaside. 2).* marks the 28 d design value of compressive strength.

2. Experimental method

2.1. Engineering information of research

Table 1 shows the engineering information of concrete structures from tropical atolls. CAC structures on Eneu of the Bikini Atoll of the Marshall Islands in the Pacific include communication buildings, powerhouse bunkers, and timing bunkers. On Kwajalein Atoll of the Marshall islands are located a CAC breakwater and Building A (Japanese blockhouse during the Second World War). CAC structures on the Saipan battlefield of the Mariana Islands include the frame-structured building B (Japanese communication building from the Second World War) and cave building C (Japanese headquarters during the Second World War). Meanwhile, OPC structures in the Paracel Islands of the South China Sea include an abandoned garage, cement mortar over prefabricated steel mesh, and building D (Miniature changing room), while CAC structures there include a lighthouse and breakwater.

2.2. Analytical method

2.2.1. Rate of reinforcement corrosion

The rate of reinforcement corrosion was calculated according to the ASTM G1-1990 *Standard practice for preparing, cleaning, and evaluating corrosion test specimens*. De-rusting steps were as follows: pickling in 12% (mass percent) HCl solution, rinsing with water, neutralizing with saturated $Ca(OH)_2$, and rinsing thoroughly with water. After wiping, drying, and storing for at least 4 h, the concrete was weighed by an analytical balance.

$$L_w = \frac{d{\cdot}l - m}{d{\cdot}l} \times 100\% \tag{1}$$

where L_w is the rate of the reinforcement corrosion (%),d is the nominal diameter of the reinforcement (mm), l is the linear density of the reinforcement (g/mm), m is the quality of the reinforcement after pickling (g).

2.2.2. Nominal yield strength, nominal ultimate strength, and elongation of the reinforcing steel

According to the ASTM E8M-2004 *Standard test methods for tension testing of metallic materials*, the nominal yield strength, nominal ultimate strength, and elongation of the reinforcing steel were calculated.

2.2.3. Cl^- concentration

According to the ASTM C1138M-2005 *Standard test method for abrasion resistance of concrete*, As for structure exposing for different time, hole drilling method was employed to collect the powder of the surface of the structure, making use of a drill with diameter of 6 mm. Different powder specimens were collected on the spot, including 0–5 mm, 5–15 mm, 15–25 mm, 25–35 mm, 35–55 mm, 55–65 mm, 65–75 mm, 75–85 mm, 85–95 mm and other depths. Then the coarse particles were removed through the griddle with the 0.15 mm pore size. the free Cl^- concentration (C_f) and total Cl^- concentration (C_t) of powder specimens from different depths as collected by drilling in the field were analysed through water-soluble and acid-soluble methods. The chloride in the concrete can be divided into two types: one is the free chloride (C_f), which is dissolved in the water of the pore; the other is the binding chloride (C_b), which is absorbed on the pore surface or combined with the cement hydration products through physical or chemical effect. The total chloride (C_t) is the sum of the free chloride and the binding chloride.

$$C_b = C_t - C_f \tag{2}$$

where C_t is the total chloride concentration of the concrete (%), C_f is the free chloride concentration of the concrete (%), C_b is the binding