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Development of properties and microstructure of concrete with coral reef sand under sulphate attack and drying-wetting cycles

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HIGHLIGHTS

- Ettringite and Friedel's salt formed in concrete with CRS after sulphate attack.
- Ettringite formed in concrete prepared with river sand after sulphate attack.
- Concrete prepared with coral reef sand intakes more sulphate, forming more ettringite.
- Salt concentrations have marginal effects on mass change of concrete with CRS.
- Loss of elastic modulus of concrete with CRS is smaller due to formation of ettringite.

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ABSTRACT

Coral reef sand is natural abundant solid resource on islands in the tropical region and is often used in the construction projects as fine aggregates where natural river sand is rare. The concrete structures on islands are usually subjected to drying-wetting cycles from sea-water due to the waves and tides, resulting in the deterioration of durability. In this study, Portland cement concrete is prepared with coral reef sand (CPC) and the effects of combined attack of drying-wetting cycles and sulphate are investigated and compared to concrete made with natural river sand (NPC). The corrosion products are ettringite and Friedel's salt for CPC and ettringite for NPC. More ettringite forms in the pores of CPC by immobilizing more sulphate from Na_2SO_4 solution, which causes strength loss of both CPC and NPC concrete. The salt concentrations have marginal effects on the mass change of CPC concrete. The loss of elastic modulus of CPC concrete is smaller than that of NPC concrete, due to the precipitation of ettringite in the pores of concrete, which compacts the structure of concrete.

1. Introduction

Portland cement concrete has been widely used in the offshore construction projects due to the advantages of low cost and great resistance to seawater corrosion compared to steel. Most offshore infrastructures such as pavement, buildings, dams and harbours are manufactured with concrete. Normal concrete is consist of Portland cement, river sand, gravels, chemical admixtures and water [1]. However, the transportation of river sand to the offshore construction sites greatly adds to the costs. Some offshore construction projects are planned on islands of which the major rocks are composed of coral reefs. [2]. The coral reefs are relics of dead corals accumulated in the past hundreds of years [3]. It is a rich solid resource on islands typically in the tropical region and is often used in various construction projects where natural dense rocks are rare [4].

The Coral Reef Sand (CRS) is a natural abundant solid resource on islands in the tropical region and is often used in the construction projects as fine aggregates. Preparation of Portland cement concrete with coral reef sand has become a major interest for construction on tropical islands in recent years as the coral reef is porous by nature and the elastic modulus is relatively low compared to natural river sand (NRS) [5–7]. If NRS is completely replaced by CRS on an equal mass basis, the fresh concrete mix becomes stiff and its slump is significantly reduced due to the high water demanding of porous low-density CRS [5]. The compressive strength of concrete prepared with CRS is close to that of concrete

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Table 1
Oxide compositions of CRS and Portland cement (wt%).

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	Cl^-	LOI*
CRS	50.46	0.42	0.17	N.D	3.1	0.43	0.35	–	0.024	44.6
Cement	58.81	21.9	5.36	2.89	2.3	2.36	0.7	0.25	N.D.	3.66

Note: LOI: Loss on ignition at 1000 °C.
N.D.: Not detected.

prepared with NRS if the concrete is designed with a compressive strength of no higher than 50 MPa. Producing concrete with strength higher than 50 MPa is difficult by CRS [2]. The strength development of concrete prepared with CRS is rapid compared to that with NRS, but the strength gain during late age is slower, and the long term strength is comparable to that of concrete with NRS if the concrete is designed for medium strength (30–50 MPa) [5,7–9]. One of the major challenges of using CRS in concrete is the corrosion of steel rebar in the reinforced concrete structure, caused by the chlorides in the coral reef and its porous permeable nature [10,11].

The concrete structures on islands are often subject to drying-wetting cycles from sea-water due to the waves and tides. It has been reported that the deterioration of concrete is greatly accelerated in the tides zone of structure compared to the under-water and dry zones. The main hydration products of Portland cement are the calcium silicate hydrates (C–S–H), Portlandite, calcium aluminate hydrate and ettringite [12]. In the marine environment and when sulphates in seawater migrate into the hardened concrete, dihydrate gypsum is formed with the promoted formation of ettringite. With the presence of Mg^{2+}, solid $Mg(OH)_2$ is formed as well in the pores filled with alkaline solution. The expansion associated with the formation of gypsum, ettringite and brucite causes the spalling of concrete from the surface of structures [13–16]. The drying-wetting cycles in salt solution aggravates the attack of sulphate and magnesium as they enhance the migration of ions into concrete, and the drying process concentrates the ions in the pores [17].

The microstructure of Portland cement concrete prepared with CRS is remarkably different from that of concrete with NRS [2]. It is expected that the deterioration process of concrete with CRS after drying-wetting cycles is different as well, of which research is rare yet. Investigation of the deterioration process of concrete with CRS after drying-wetting cycles in salt solution simulating the seawater can thus provide useful data for evaluating the service life of structures in the tropical region where CRS is used.

In this study, Portland cement concrete is prepared with CRS and its performance under the combined attack of drying-wetting cycles and sulphates is compared to that of concrete prepared with natural river sand. The mass and strength development, microstructure and phase evolvement are characterized by a range of analytical techniques, aiming to reveal the mechanism of differences between the performance of these two concrete under the attack of drying-wetting cycles and sulphate.

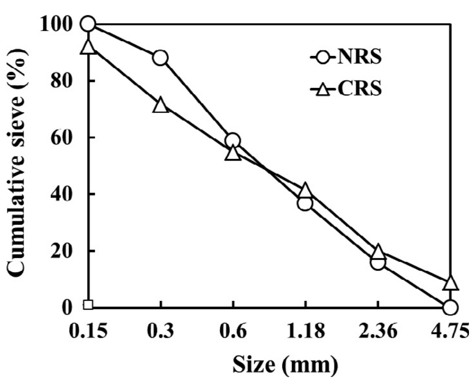

Fig. 1. Grading curve of NRS and CRS.

2. Materials and experimental

2.1. Materials

Ordinary Portland cement (OPC) is used, with a strength grade of 42.5 classified as P.O. 42.5 complying with the Chinese standard GB 197-2007. The oxide compositions of OPC are listed in Table 1. Crushed limestone gravel is used as the coarse aggregate with particle sizes ranging of 5–25 mm. A poly-carboxylate ether based superplasticizer (SP) containing 40% solids by mass and with a water-reducing rate of 26% is used. Fresh tap water is used as mixing water.

Two types of sand are used for preparing concrete, namely CRS and NRS. The oxide compositions of CRS are listed in Table 1. It is noteworthy that the CRS contains some chloride. The particle size distributions of the two types of sand are shown in Fig. 1. Physical properties of the two types of sand are listed in Table 2, which are tested according to the Chinese standard GB/T 14,684-2011 [18]. Both the packing density and apparent density of CRS are lower than those of NRS due to the much higher porosity of CRS comparing to NRS, resulting in both higher water absorption rate and crush value.

After CRS is dried and ground, X-ray diffraction (XRD) pattern is obtained and analysed by Bruker D8 Advance under the conditions of Cu Kα = 1.5406 Å, step size of 0.02°, measuring time of 15 s/step, start position 5° and end position 80°. The main minerals in CRS are aragonite and calcite (rich in Mg) (Fig. 2).

The microstructure of the CRS is observed with scanning electron microscopy (SEM, model JSM-5610LV) and shown in Fig. 3. The surface of CRS is rough and porous, in agreement with the results of apparent porosity and water absorption rate.

Mix proportions of concrete prepared with both the CRS and NRS are listed in Table 3, namely CPC and NPC, respectively.

Table 2
Physical properties of CRS and NRS.

Type	Packing density (kg/m^3)	Apparent density (kg/m^3)	Water absorption rate (%)	Apparent porosity (%)	Crush value (%)
CRS	1320	2350	5.78	42.6	44
NRS	1560	2600	1.50	35	17.5