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Strength and durability of coconut-fiber-reinforced concrete in aggressive environments

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HIGHLIGHTS

- ▶ Closing the gap of knowledge on the applications of FRC in the aggressive.
- ▶ Concept of FRC is potential in countering aggressive environments.
- ▶ Natural fiber is not suitable to apply in marine exposure condition.

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ABSTRACT

Marine structures have suffered from seawater attacks for decades. Thus far, the best approach to minimize the deleterious effects on these structures is to use high-strength, high-performance concrete. However, this approach has its limitations. When a crack starts because of the expansion and shrinkage at splash zones and expansive products are formed because of sulfate attacks, the crack will grow and propagate uncontrollably. Ultimately, the durability of the structure is drastically reduced. The aim of this experiment is to mitigate this limitation by incorporating short, discrete coconut fibers into high-strength concrete. This method is based on the idea that the localized reinforcing effect provided by the discrete fiber can restrain the development of cracks caused by aggressive environments. The structures were exposed to three types of aggressive environments: air environment in a tropical climate (A-series), alternate air and seawater environments in a 14-day cycle (4 days wetting + 10 days drying) (N-series), and continuous immersion in seawater (W-series). Compressive and flexural parameters were used to examine the strength of each structure, while chloride penetration, intrinsic permeability, and carbonation depth were used to examine their durability properties. The mineralogy and microstructure were studied by means of X-ray diffraction and scanning electron microscopy examinations. The experimental results prove that the compressive and flexural strengths of the structures improve up to 13% and 9%, respectively, with the incorporation of coconut fibers. However, in terms of durability, the chloride penetration, intrinsic permeability, and carbonation depth increase with the increase in fiber content. Most importantly, in the intrinsic permeability, the plain specimen in the N-series showed a sudden increase in intrinsic permeability when the exposure period increased from 365 days to 546 days. This result signifies that the fibers play a role in restraining the development of cracks. In general, the deleterious effects brought about by aggressive environments can be suppressed with fiber-reinforced concrete. However, the dosage of coconut fiber should be low, not exceeding 1.2% of the binder volume, due to the drawback of its natural degradation. This study recommends that the coconut fiber undergo treatment prior to its application in concrete to protect it against degradation or that it be replaced with a non-corrosive fiber.

1. Introduction

Strength and durability are often regarded as the most important criteria in concrete structure designs. These criteria especially apply for marine structures, which are exposed to hazardous environments and used in heavy-duty tasks such as resisting abrasion and erosion from ocean waves, high loading for shipments, and high seismic loading from the collision of water transports to the structure, among others. High-strength concrete (HSC) has, therefore, become the first choice of construction material for marine structures. The durability of concrete may refer to its ability to resist quality degradation when exposed to environments that cause deleterious effects to the concrete [1,2]. When dealing with a seawater environment, engineers may have to pay extra attention due to the severe attacks on the

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Table 1
Chemical composition of ordinary Portland cement and silica fume according to manufacturer's detail.

Percentage by weight		
Constituent	Ordinary Portland cement	Silica fume
Lime (CaO)	64.64	1.0% (max)
Silica (SiO_2)	21.28	90% (max)
Alumina (Al_2O_3)	5.6	1.2% (max)
Iron oxide (Fe_2O_3)	3.36	2.0% (max)
Magnesia (MgO)	2.06	0.6% (max)
Sulfur trioxide (SO_3)	2.14	0.5% (max)
Nitrogen oxide (N_2O)	0.05	0.8% (max)
Loss of ignition	0.64	6% (max)
Lime saturation factor	0.92	–
C_3S	52.82	–
C_2S	21.45	–
C_3A	9.16	–
C_4AF	10.2	–

Table 2
Specifications of coconut fiber.

Item	Unit	Test value
Diameter	mm	0.32
Length	mm	20–30
Tensile strength	MPa	176
Elastic modulus	GPa	22.4
Specific gravity	–	1.13

concrete structure. These attacks include chloride attack, sodium sulfate and magnesium sulfate attack, rapid expansion and shrinkage at the splash zone, salt crystallization, abrasions and erosions by the waves, and so on [2–5]. For most of these attacks, the results of the attacking mechanism are frequently related to the initiation of cracks due to the volume changing or expansive nature of the reactions' products [5,6]. The tropical climate is relatively less severe than the seawater environment. However, the hot and humid environment may aggravate the process of carbonation. Temperature change during the switch from rainy to sunny day, or vice versa, may also cause the concrete to suffer because of expansion and shrinkage.

Existing literature has reported several benefits of the incorporation of short, discrete fibers into concrete. Randomly distributed fibers in the concrete can enhance the toughness, ductility, and integrity of the matrix, shear strength, energy absorption capacity, and damage tolerance in flexural, among others, of the concrete [7–11]. Other researchers have also highlighted that fibers can delay the crack propagation and improve the distribution stress in the matrix upon loading [12,13]. In addition, researchers have learned that short fibers are effective in addressing the volume changing issue [14,15]. Therefore, the idea of this study is to evaluate the contribution of fiber in HSC in terms of the strength and durability parameters when the fiber-reinforced concrete is exposed to a seawater environment and tropical climate. This study also aims to close the research gap between the applications of fiber-reinforced concrete in aggressive environments. Previous studies on concrete in aggressive environments focused on the binary or ternary blended cement system [1–6]. Studies on the concept of using discontinuous fiber to address the aggressive environment issues are scarce [10,13]. The selection of coconut fiber is in conjunction with the sustainability concept and the fact that the sources are abundant in Malaysia.

Table 4
Strengths and permeability of various specimens at 28 days [16].

Specimens	Compressive strength (MPa)	Flexural strength (MPa)	Intrinsic permeability ($\times 10^{-16}$ m^2)
CTRL	71.78	5.21	0.31
0.6CF	74.00	5.29	1.36
1.2CF	73.40	5.57	3.28
1.8CF	73.41	6.15	3.49
2.4CF	72.96	5.97	4.19

Table 5
Major ions of sea water.

Ion	Fresh sea water (mg/L)	Used sea water (mg/L)	Typical sea water (mg/L)
Chloride	20265.8	17055.6	18,980
Bromide	48.1	39.7	65
Phosphate	5.8	8.3	–
Sulfate	2250.2	1929.8	2950
Magnesium	309.5	5.8	1262
Calcium	283.5	711.5	400
Potassium	414.0	644.71	380

2. Experimental program

Type I Portland cement and condensed silica fume were used as the binder course for the experiment. The chemical compositions of both cement compounds are illustrated in Table 1. River sand was sieved to obtain the size range of 600 μm to 4.75 mm. Sieving increases the fineness modulus of sand. In this study, the specific gravity and fineness modulus of the river sand were 2.51 and 3.98, respectively. Crushed granite with a specific gravity of 2.7 and a nominal size of 19 mm was used as coarse aggregate. A chloride-free super plasticizing admixture based on sulphonated naphthalene polymers, which complies with BS 5075, was added to enhance the workability. Coconut fiber was incorporated at four different contents, i.e., 0.6%, 1.2%, 1.8%, and 2.4%, into the concrete. The percentage of fiber content was calculated based on the binder volume. The specifications of the coconut fiber are shown in Table 2. Table 3 illustrates the mix proportions for all mixes. There are a total of five mixes. The control specimen is denoted as CTRL, while the 0.6CF, 1.2CF, 1.8CF, and 2.4CF are denoted according to the volume of fiber incorporated.

This experimental investigation is the continuation of another work. The previous study has established the strengths and permeability achieved by various coconut fiber mixes (CF series) at 28 days. The results will be summarized in Table 4 [16]. This part of the experimental work examined the long-term strengths and durability of the CF series. The CF series specimens that were at first cured in normal water conditions for 28 days were taken out and exposed to three different environments: air (A-series), alternate air and seawater (N-series), and seawater (W-series). The A-series resembles the tropical climate conditions, where the specimens were placed outside the laboratory and subjected to sun radiations and rains. The N-series specimens were subjected to a 14-day cycle of wetting and drying, 4 days in seawater and 10 days in air environment like the A-series. For the W-series, all of the specimens were continuously submerged in seawater until the age of testing. The specimens were exposed to three environments for a period of 90, 180, 365, 546 days or 3, 6, 12, and 18 months. The major ion composition of the respective seawater analyzed by the chromatographic method is illustrated in Table 5.

Table 3
Mix proportions of various specimens.

Specimens	Cement (kg/m^3)	Silica fume (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Superplastiziser (kg/m^3)	Coconut fiber (kg/m^3)
CTRL	435.6	59.4	183	689	1033	9.9	–
0.6CF	435.6	59.4	183	689	1033	9.9	1.12
1.2CF	435.6	59.4	183	689	1033	9.9	2.24
1.8CF	435.6	59.4	183	689	1033	9.9	3.36
2.4CF	435.6	59.4	183	689	1033	9.9	4.48