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Axial compressive behavior of seawater coral aggregate concrete-filled FRP tubes

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HIGHLIGHTS

- SCAC-filled FRP tubes are highly attractive for applications in marine constructions.
- The paper presents an experimental study on SCAC and SCAC-filled FRP tubes.
- The performance of SCAC with or without FRP confinement is different from OAC.
- An extended stress-strain model for FRP-confined SCAC is developed.

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ABSTRACT

The use of seawater coral aggregate concrete (SCAC) instead of ordinary aggregate concrete (OAC) in concrete-filled FRP tube (CFFT) members is highly attractive due to the beneficial effect of fiber-reinforced polymer (FRP), which has good resistance to salt and can effectively counteract the greatest shortcomings of the chloride-containing ions in SCAC. In the development of marine construction, SCAC-filled FRP tubes are a potential attractive alternative for pile and column applications in corrosive marine environments. The axial compressive behavior of SCAC-filled FRP tube (SCFFT) was first experimentally investigated and compared with OAC-filled FRP tube (OCFFT) in this study. The chosen coral aggregates (CAs) and SCAC were systematically prepared and tested, including classification and materials testing on CAs, uniaxial load testing on SCAC and microstructure analysis of SCAC. The porous nature and low strength of CAs led to a different and brittle failure mechanism of SCAC under uniaxial loading, and result in SCAC experiencing a compacting behavior before the development of its rapid expansion and the activation of confinement in SCFFT. As a consequence, the axial loading of SCFFT displayed a slight drop in the transition zone for the range of axial strains between approximately 0.002 and 0.004. The non-homogeneity and brittleness of SCAC led to a non-uniform hoop strain distribution in SCFFT under compression and thus discounted the effect of confinement. The ultimate load of SCFFT was approximately 60% of that of its OCFFT counterpart. The key elements and basic framework used to develop a detailed analysis-oriented model for predicting FRP-confined SCAC under axial compression was illustrated. Furthermore, the model developed originally for FRP-confined lightweight concrete with ceramsite aggregates was extended to cover FRP-confined SCAC, and the extended model was confirmed to be capable of producing reliable predictions.

1. Introduction

The use of coral reefs as aggregates for concrete began prior to World War II. Coral reefs are a type of organic sedimentary rock. The bulk of coral reefs are held together by calcium carbonate structures that are secreted by corals, which consist of 95–99% calcium carbonate [1]. Some investigative reports in the literature have affirmed that coral reef material is suitable as an aggregate for concrete [1–3], but it was thought to be a reluctant last resort to the shortages of raw materials for construction in the islands. The presence of salt in coral reefs can lead to the corrosion of embedded steel and the destruction of the concrete structure [4,5]. Currently, the concept of using coral reefs in concrete is believed to be much more practicable because materials with superior anti-corrosion to salt, such as fiber reinforced polymer

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(FRP) tubes [6–8], bars [9], grids [10], and pultrusions [11,12], are increasingly used as reinforcement in concrete construction. Among these application forms, the concrete-filled FRP tube (CFFT) has been extensively studied and recognized since it was introduced 20 years ago [13]. It is well known that confinement of FRP composites substantially enhances the compressive strength and ultimate strain of concrete. With the same concept, the combined use of seawater coral aggregate concrete (SCAC) and FRP tubes offers many more advantages, especially in the development of marine construction. Locally available materials, including coral reefs, seawater, and sea sand, can be used directly in cast concrete and filled in FRP tubes to avoid the long-distance marine transportation of imported mainland materials and support the construction schedule. The FRP tube serves as a permanent framework and offers anti-corrosion protection. These advantages are suitable for limited construction conditions [14] and aggressive corrosive environments. Therefore, SCAC-filled FRP tubes are a potential attractive alternative for pile, column, and bridge pier applications in corrosive marine environments.

Certain feasibility studies on coral aggregate concrete were conducted by Dempsey in 1951 in America [15], Vines in 1982 in Australia [2], and Wang in 1988 in China [16]. These trial experimental results all indicated that coral reefs were suitable for use in concrete. Additionally, seawater was studied and identified as suitable for use with coral aggregates in concrete [17]. The acceptable workability and required strength were accessible for coral concrete but generally necessitated an adjustment in the mix proportion, e.g., an increasing water amount and cement contents compared with ordinary aggregate concrete [15]. Coral reefs have been attempting applied as aggregates for concrete in practical projects for a long time. Howdyshell [1] conducted an overall investigation of coral concrete vertical construction and structures on several North Pacific islands that have been conducted by the American Navy Civil Engineer Corps since World War II. The investigative report indicated that coral has been used successfully as an aggregate for concrete in vertical construction, but in some cases, the cracking and spalling of concrete associated with corroded reinforcing steel was quite severe and affected the structural integrity. Rick [18] also conducted an overall investigation on three coral concrete structures at Bikini Atoll, including field inspection, core sampling and laboratory testing. The test results indicated that coral aggregates and seawater can be used to create quality concrete and that the durability of coral concrete itself is good, exhibiting a 55–60% increase in strength after 11 years. Based on the previous feasibility study and attempted applications, more comprehensive studies on coral aggregate concrete were systematically conducted. Arumugam and Ramamurthy [3] systematically investigated the physical, chemical and mechanical properties of coral aggregates (CAs). The results indicated that CAs have higher water absorption, a rougher surface texture, a peculiar shape, higher values of elongation and flakiness indices, lower density, lower fineness modulus of coral sand, and higher crushing, impact, and abrasion values compared with the results of tests on conventional ordinary aggregates (OAs). In particular, the crushing, impact and abrasion values were much higher than the upper limits for use in concrete wear surfaces [3]. This disadvantage can be eliminated by using FRP tubes as the outside package of SCACs. Coral aggregate concrete (CAC) was also studied, and the workability and compressive strength characteristics of different mixes of ordinary aggregate concrete (OAC) and coral aggregate concrete (CAC) have been compared and discussed. CAC exhibited a relatively lower workability and lower strength than the corresponding ordinary aggregate concrete (OAC). It was suggested that a new mix design table and better mix-proportioning procedures should be developed for coral concrete. Studies on CAC and CAs have been extensively conducted in China since 2008, and the basic characteristics properties of CAs were better realized [19–21]. The mechanical properties of CAC in different strength grades were tested by Da et al. in 2016 [22], who found that the failure mechanism of CAC is tremendously different from that of OAC. The stress-strain curves of SCAC were also found to be different from that of OAC, especially in the ascent stage. The failure mechanism of SCAC under uniaxial compression exhibited obvious brittleness. The stress after peak rapidly decreased to 0.30–0.50 of peak stress. Because SCAC was used in CFFTs, this type of brittle failure mechanism and complete spalling failure mode can be prevented by the FRP tube package. However, the failure mechanism of SCAC might have a negative impact on the confinement of the FRP tube, which must be investigated. Although these research results offer valuable reference information on the use of coral reef as an aggregate in concrete, limited test data are available on both CAs and SCAC. In this study, the properties of CAs and SCAC were systematically investigated in a comprehensive experimental research study.

The use of SCAC instead of OAC in CFFT members is highly attractive because the beneficial effect of FRP's good resistance to salt can effectively counteract the largest shortcomings of the chloride-containing ions in SCAC [23]. As noted previously, SCAC-filled FRP tubes (SCFFTs) are highly suitable for marine construction. To the best of the authors' knowledge, no experimental study has yet been reported on the behavior of SCFFTs under compression. However, a considerable amount of experimental research has been conducted on the performance of CFFTs under compression in recent years, and various aspects of this composite system have been systematically investigated [24]. The experimental and analytical studies have led to a good understanding of the behavior of CFFTs using OAC under axial compression, and these studies delivered a comprehensive research foundation on which to study CFFTs using SCAC. Therefore, this study compares the CFFT using SCAC with that using OAC under axial compression to identify the differences and similarities. The objective is to understand the mechanism of FRP-confined SCAC based on the well-understood confinement mechanism of FRP-confined OAC [25,26].

A large number of models have been developed over the past two decades to predict the stress-strain behavior of FRP-confined OAC under axial compression [27–29]. An analysis-oriented model proposed for FRP-confined OAC, which is widely recognized as producing the best prediction [29], was compared with the experimental results from SCFFT. Although the model is not anticipated to be suitable for FRP-confined SCAC because the mechanical properties of SCAC are tremendously different from those of OAC, the basic framework and key elements used to develop an analysis-oriented model for FRP-confined SCAC under axial compression contribute to a greater overall understanding such that the next-step work for analysis-oriented modeling can be determined. More interestingly, some axial compressive experiments on FRP-confined ceramiste concrete were recently conducted by Zhou et al. [30]. Both SCAC and ceramiste concrete belong to the class of lightweight aggregate concrete (LWAC) and have similar mechanical properties. The modeling analysis for FRP-confined ceramiste concrete offered a reliable foundation on which to extend a design-oriented model for FRP-confined SCAC under the currently limited experimental studies.

2. Raw materials and preparation

2.1. Coral aggregates (CAs)

2.1.1. Classification and definition

The multitude of forms in which coral occur are tremendous, ranging from unconsolidated deposits of beach sand to dense reef deposits of consolidated limestone [1]. The establishment of a clas-