Cube Strength Test of Hybrid Fiber Reinforced Alkali-Activated Coral Concrete

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Abstract. In remote ocean reefs, coral concrete made from local materials could be used as an alternative to traditional concrete. However, the application of coral concrete is limited by its low strength, high brittleness, and poor durability. To address this issue, researchers have developed alkali-activated coral concrete (AACC) by replacing cement with alkali-activated binders made from industrial waste materials and alkaline activators, thus enhancing the durability of coral concrete components. Despite the durability advantages of AACC, it still suffers from low strength and high brittleness. To improve these deficiencies, this study incorporated stainless steel fibers (SSFs) and polypropylene fibers (PEs) to enhance the strength and toughness of AACC. Compression and splitting tensile tests on hybrid-fiber reinforced alkali-activated coral concrete (HFRAACC) cubes were conducted. The focusing on the effects of single-fiber dosage, hybrid-fiber dosage, and the hybrid-fiber ratio on strength. The experimental results indicate that the inclusion of hybrid fibers significantly improves the failure modes and working performance of the specimens. When single fibers are added, the reinforcing effect of SSFs increases with fiber dosage, whereas PEs exhibit only a slight reinforcing effect at low fiber dosages. With hybrid fibers, as the total fiber dosage increases, the reinforcing effect on compressive strength diminishes, while the reinforcing effect on tensile strength improves. Furthermore, the hybrid-fiber ratio is a crucial factor influencing the reinforcing effects, with a higher SSF-to-PE ratio yielding more significant improvements. The strength of coral concrete also affects the overall enhancement provided by the hybrid fibers.

Keywords: Coral Concrete, Alkali-Activated, Hybrid Fiber, Mechanical Property, Green Building Materials.

1 Introduction

In recent years, nations worldwide have been constructing marine and reef engineering initiatives on remote islands and reefs to protect marine ecology while achieving sustainable development of marine resources. On remote islands and reefs,

W. Guo et al. (eds.), *Proceedings of the 3rd International Conference on Green Building, Civil Engineering and Smart City (GBCESC 2024)*, Advances in Engineering Research 264,
https://doi.org/10.2991/978-94-6463-728-1_7

there is a shortage of sand, fresh water, and cement as building materials. Therefore, using coral debris as a substitute for sand and seawater instead of fresh water to produce coral aggregate concrete (CAC) can reduce construction costs [1]. However, the application of CAC is limited by its inherent low strength, brittleness, and limited durability in complex marine environments and infrastructure construction [2].

Both traditional concrete and CAC use cement as the cementitious material, and the production process of cement generates a large amount of CO_2 emissions. To reduce cement usage, researchers have developed alkali-activated cementitious materials using industrial waste and alkaline compounds to replace cement, thus producing alkali-activated concrete (AAC) [3-4]. Compared to traditional concrete, the alkaline activator activates silicon- and aluminum-rich precursors, forming a dense microstructure. This structure reduces the porosity in both the coral aggregates and AAC. Additionally, the high alkalinity of AAC helps resist chemical attacks from acids and sulfates, thereby improving the durability of concrete structures [5-7]. Consequently, researchers have successfully developed alkali-activated coral concrete (AACC) by using alkali-activated cementitious materials instead of cement, significantly enhancing the strength and durability of CAC [8-9]. However, even AACC still struggles to meet the demands of complex marine environments. Therefore, further improvements in the toughness and impact resistance of AACC components are necessary.

The incorporation of single fibers or hybrid fibers into concrete can enhance the toughness and impact resistance of concrete components. This study used a mixture of corrosion-resistant stainless steel fibers (SSFs) and highly durable polyethylene fibers (PEs) as reinforcing and toughening fibers. It replaces cement with alkali-activated cementitious materials made from mineral powder and waste marble powder to produce green, high-toughness, hybrid fiber-reinforced alkali-activated coral concrete (HFRAACC). This study aimed to investigate the effects of hybrid fiber dosage, the ratio of SSFs to PEs, and concrete strength on basic mechanical properties, providing foundational data for future studies on other mechanical properties.

2 Experimental

2.1 Raw Materials

The alkali-activated cementitious material consists of two parts: a precursor and an alkali activator. The precursor materials are ground granulated blast furnace slag (GGBFS) and waste marble powder (WMP). The alkali activator is a mixture of water glass (sodium silicate solution) and flake sodium hydroxide. The coarse aggregates used consisted of continuously graded coral fragments, graded 5~20 mm, with a compressive strength of 2.51 MPa. The fine aggregate was coral sand with a fineness modulus of 3.14. Artificial seawater was used as the mixing water for the concrete. The fibers used included stainless steel fibers (SSFs) and polyethylene fibers (PEs), and the detailed parameters are listed in Table 1. Additionally, a naphthalene-based superplasticizer and P803 powder defoamer were used. The appearance of the raw material is shown in Fig. 1.

Table 1. Physical and mechanical properties of the fibers

Name	Length/mm	Diameter/μm	Aspect ratio	Density/(g/cm3)	f_t/MPa
SSFs	13	200	65	7.89	2000
PEs	18	24	750	0.97	2900

2.2 Specimen design

In this study, 25 sets of HFRAACC cubic specimens with a side length of 100 mm were designed based on the amount and ratio of hybrid fibers incorporated. Cubic compressive strength and splitting tensile strength tests were conducted to investigate the effects of single-fiber and hybrid fiber incorporation on the uniaxial mechanical properties. The volume percentages of stainless steel fibers (SSFs) were 0.6%, 0.9%, 1.2%, 1.5%, and 1.8%, while the percentages of polyethylene fibers (PEs) were 0.3%, 0.6%, 0.9%, 1.2%, and 1.5%. The primary experimental group consisted of specimens with a concrete strength grade of C30. Additional concrete strength grades (C20, C40, and C50) were tested with specific fiber dosages. The mix proportions of the specimens are shown in Table 2. In this study, the specimen labeled C30-1.5-0.3 represents a concrete strength grade of C30 with an SSF dosage of 1.5% and a PE dosage of 0.3%.

Table 2. The mix proportions of alkali-activated coral concrete with hybrid fibers

NO.	Dosage/kg/m^3								W/B
	mineral powder	waste marble powder	water glass	NaOH	Amount of purified water	external water mode	Coral Aggregate	Coral Sand	
C20	196	196	136.4	25.9	234	20.7	770	819	0.52
C30	239	239	166.7	31.6	231	20.7	770	819	0.42
C40	283	283	197.0	37.4	208	20.7	770	819	0.32
C50	326	326	227.3	43.1	173	20.7	770	819	0.23

2.3 Test Method

Specimen preparation. Before preparing the specimens, the alkaline activator solution was prepared 24 hours in advance, and the raw materials were weighed according to the mix proportion of the specimens. Prior to preparation, the coral aggregates were immersed in seawater, drained after two hours, and air-dried until the surface was free of water. The procedure shown in Fig. 1 was followed for specimen preparation.

Strength test. When the curing period of the cubic specimens reaches 28 days, the TAW-3000 universal pressure testing machine is selected to conduct compressive strength tests, while a universal material testing machine is selected for the splitting tensile strength test, as shown in Fig. 2 and Fig. 3. Three specimens were selected for strength testing in each group, and the data were recorded. The loading rate during testing is set to 0.5 kN/s.

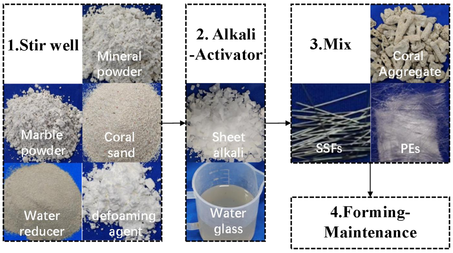

Fig. 1. Specimen preparation flow chart

Fig. 2. Axial compression

Fig. 3. Splitting tensile

3 Test results and analysis

3.1 Failure modes

Fig. 4 illustrates the failure modes of the HFRAACC cubic specimens with different fiber dosages. Fig. 4 (a) shows that without fiber incorporation, the specimen underwent rapid cracking and spalling upon compression, indicating brittle failure. With the incorporation of hybrid fibers, the specimen exhibits significant lateral deformation under compression while maintaining overall integrity. As the fiber dosage increases, the lateral deformation decreases, indicating ductile failure. Fig. 4 (b) shows that specimens without fibers experience extensive, penetrating cracks and concrete spalling upon tensile failure. However, with the inclusion of hybrid fibers, the crack width decreases with increasing fiber dosage, accompanied by significant deformation prior to failure. Overall, the incorporation of the hybrid fibers improves the brittleness of the material and enhances the deformability of the specimen.

C30-0-0 C30-1.5-0.3 C30-1.5-0.75

(a) Axial compression

C30-0-0 C30-1.5-0.3 C30-0.9-0.9

(b) Splitting tensile

Fig. 4. Failure modes of the HFRAACC specimens with different fiber dosages

3.2 Effect of single-fiber incorporation

Fig. 5 illustrates the influence of single-fiber dosage on the compressive strength f_{cc}, tensile splitting strength f_{ts}, and ratio of tensile strength to compressive strength ($f_{ts}/$

f_{cc}) of HFRAACC. The complete data can be found in the Attached Table 1. In this study, the specimens without concrete strength indicated were all C30. As shown, with increasing SSF dosage, f_{cc}, f_{ts} and f_{ts}/f_{cc} initially increase and then decrease. This indicates simultaneous improvement both in compressive and tensile properties. Conversely, PEs exhibit enhancing effects only at low dosage levels. Beyond 0.9%, PEs exhibit a weakening effect on the specimens. The single incorporation of PEs does not comprehensively improve the compressive and tensile properties of the material.

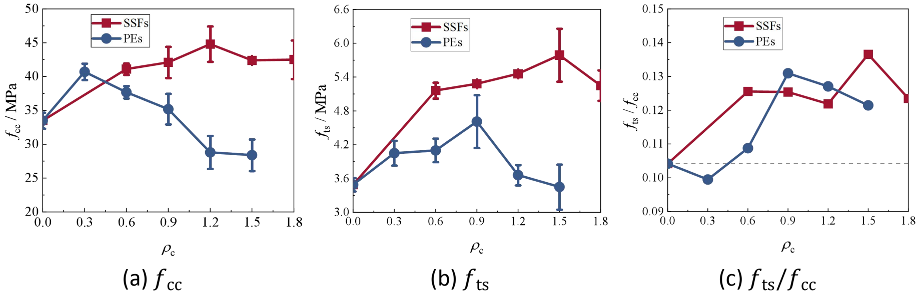

Fig. 5. Effect of single-fiber dosage on strength

3.3 Effect of hybrid fiber incorporation

Fig. 6 illustrates the influence of the total hybrid fiber dosage and the fiber dosage ratio on the f_{cc}, f_{ts} and f_{ts}/f_{cc} of the HFRAACC samples. As shown, when the fiber dosage ratio (SSFs: PEs $=\rho_1:\rho_2$ = 2:1) remains constant, f_{cc} decreases gradually while f_{ts} and f_{ts}/f_{cc} increase with the increase in total fiber dosage. This indicates that the weakening effect of high-dosage PEs outweighs the enhancing effect of high-dosage SSFs. Although the compressive performance may decrease, the tensile properties is significantly improved. When the total hybrid fiber dosage is 1.8%, with increasing fiber dosage ratio, the reinforcing effect of the hybrid fibers gradually improves but remains weaker than that of single SSFs. This suggests that regardless of the total hybrid fiber dosage, PEs weaken the enhancing effect of SSFs on strength. As the total hybrid fiber dosage increases, f_{cc}, f_{ts} and f_{ts}/f_{cc} all increase gradually, indicating that high-dosage SSFs and low-dosage PEs better enhance the strength of the material.

3.4 Effect of the concrete strength

Fig. 7 illustrates the impact of the concrete strength on the HFRAACC cubes f_{cc}, f_{ts}, and f_{ts}/f_{cc}. As shown, at lower concrete strengths, the hybrid fibers primarily enhance the strength of the sample f_{ts}. With increasing concrete strength, the reinforcing effect of the hybrid fibers on sample f_{cc} significantly improves. The variation in sample f_{ts}/f_{cc} indicates that as the strength of the coral concrete increases, the brittleness increases, affecting the comprehensive reinforcing effect of the hybrid fibers. However, it still comprehensively improves the strength and toughness of the material.

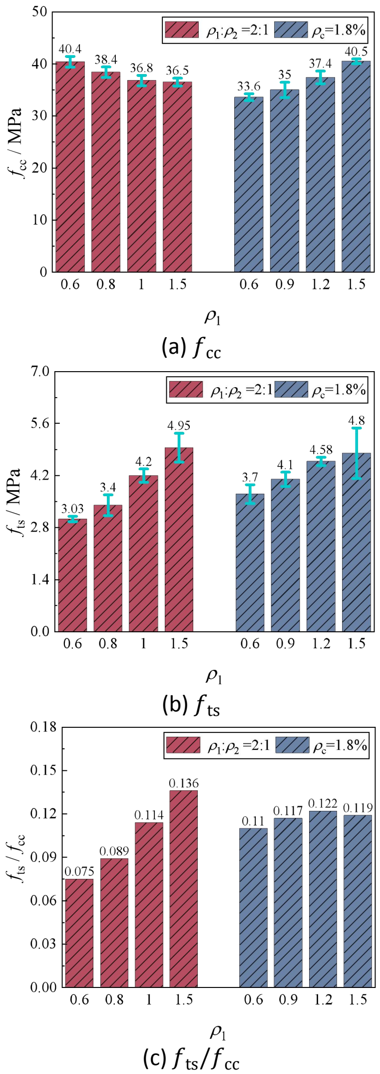

Fig. 6. Effect of the hybrid fiber dosage and dosage ratio on the strength

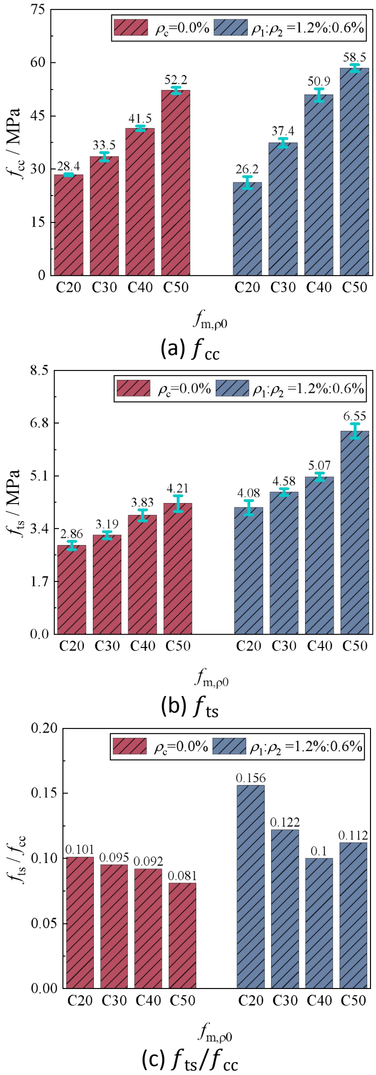

Fig. 7. Effect of the concrete strength on the hybrid fiber reinforcement

4 Conclusion

This study selected two types of fibers, stainless steel fibers (SSFs) and polyethylene fibers (PEs), and focused primarily on the concrete strength grade C30 in the experiments. The main research investigated the effects of single-fiber dosage, hybrid-fiber dosage, and hybrid-fiber dosage ratio on the strength of HFRAACC cubic specimens. The main conclusions are as follows:

1. The combination of strengthening fiber SSFs and toughening fiber PEs improved the deformability of the HFRAACC specimens under compression and splitting tensile failure. Compared to specimens without fiber incorporation, hybrid fiber specimens exhibited significant deformation before failure, with fine and closely spaced cracks while maintaining overall integrity.
2. The single incorporation of SSFs significantly enhanced the compressive strength and splitting tensile strength of the HFRAACC specimens, with the enhancement effect increasing with increasing fiber dosage. In contrast, PE fibers exhibited enhancement effects only at lower dosages.
3. With an SSF to PE dosage ratio of 2, the enhancement effect of the hybrid fibers on the compressive strength (f_{cc}) and splitting tensile strength (f_{ts}) of the HFRAACC specimens decreased and increased, respectively, with increasing hybrid fiber dosage. When the total hybrid fiber dosage reached 1.8%, the enhancement effect of the hybrid fibers became more significant with increasing SSF-to-PE dosage ratio.
4. At higher strengths of coral concrete, the enhancement effect of hybrid fibers was significant, but the overall enhancement performance weakened.
5. HFRAACC can be used as a green building material in structural engineering and marine engineering.

Appendix

Table 1 Compressive and splitting tensile strength of cubes with different fiber dosages

Category	No.	f_{cc}/MPa	f_{ts}/MPa	No.	f_{cc}/MPa	f_{ts}/MPa
Without fiber	C20-0-0	28.4±0.25	2.86±0.13	C30-0-0	33.5±1.18	3.49±0.12
	C40-0-0	41.5±0.64	3.83±0.18	C50-0-0	52.2±0.87	4.21±0.25
Single fiber	C30-0.6-0	41.1±0.85	5.16±0.14	C30-0-0.3	40.7±1.21	4.05±0.22
	C30-0.9-0	42.1±2.30	5.28±0.04	C30-0-0.6	37.7±0.92	4.10±0.21
	C30-1.2-0	44.8±2.61	5.46±0.06	C30-0-0.9	35.2±2.26	4.61±0.47
	C30-1.5-0	42.4±0.21	5.79±0.47	C30-0-1.2	28.8±2.45	3.66±0.18
	C30-1.8-0	42.5±2.85	5.25±0.27	C30-0-1.5	28.4±2.33	3.45±0.40
Hybrid fiber	C30-0.6-1.2	33.6±0.65	3.70±0.25	C30-1.5-0.75	36.5±0.75	4.95±0.39
	C30-0.9-0.9	35.0±1.46	4.10±0.19	C30-0.6-0.3	40.4±1.02	3.03±0.07
	C30-1.2-0.6	37.4±1.21	4.58±0.11	C30-0.8-0.4	38.4±0.99	3.40±0.28
	C30-1.5-0.3	40.5±0.46	4.80±0.68	C30-1.0-0.5	36.8±2.29	4.20±0.18
	C20-1.2-0.6	26.2±1.70	2.86±0.13	-	-	-
	C40-1.2-0.6	50.9±1.76	5.07±0.25	C50-1.2-0.6	58.5±0.96	6.55±2.23

Acknowledgment

This study was funded by the Guangxi Science and Technology Base and Special Fund for Talents Program (Grant No. GuikeAD22035999), Guangxi Science and Technology Major Project (Grant No. GuikeAA22068073-3), the National Natural Science Foundation of China (Grant Nos. 52108201 and U22A20244), the Natural Science Foundation of Guangxi (Grant No. 2021GXNSFBA220049), the Guangxi Key Laboratory of Green Building Materials and Construction Industrialization (Grant No. 22-J-21-9).

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