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The effect of fly ash and silica fume on mechanical properties and durability of coral aggregate concrete

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HIGHLIGHTS

- The concrete aggregate is fully replaced by coral sand and coral reef rubble.
- Porous coral aggregate causes low strength and poor durability properties of concrete.
- The mechanical properties and durability of CAC incorporation of FA and SF are studied.
- The Vickers' micro-hardness test of ITZ in CAC is conducted.
- The possibility of improving the high performance of CAC and its extension application in construction is proved.

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ABSTRACT

This report presents the results of experimental work on the mechanical properties of coral aggregate concrete (CAC) containing fly ash (FA) and silica fume (SF). The aim of this study was to investigate the effects of FA and SF on the fresh and aged mechanical properties of CAC. Apart from the workability of the fresh concrete, the compressive strength, splitting tensile strength, capillary water sorptivity, chloride penetration, and micro-hardness of the interfacial transition zone (ITZ) were measured. CAC with only ordinary Portland cement as the binder was used as the control mixture. The results indicated that the cohesiveness and water retention of CAC were improved by the addition of FA and SF under the condition of equal slump. CAC showed lower compressive but higher splitting tensile strength, water sorptivity, and chloride penetration compared to normal concrete because of its porous and rough surface and the high water absorption of the coral aggregate itself. FA and SF have different effects on improving the mechanical properties, durability, and structure of the ITZ of CAC. FA had a negative effect on strength at early ages, but significantly enhanced the later-age strength, while SF had a positive effect at all ages. Similar results were obtained in the chloride penetration test. However, it was found that, besides improving the compressive strength and the splitting tensile strength, the combination of FA and SF had a positive effect in reducing the water sorptivity and chloride permeability, as well as improving the micro-hardness in the ITZ, of CAC. The above properties of CAC containing 25% FA and 5% SF as partial replacements for cement are superior to those of CAC containing 5% SF alone.

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1. Introduction

In recent years, the exploitation of coral reef areas for construction resources has become increasingly common worldwide. Coral reef islands are distant from mainland, leading to increased manpower and financial resources consumed when building materials are transported from the mainland. In coral reef island countries, like the Maldives, concrete materials must be imported from abroad, which is high in cost. Coral reef calcareous sand as a specific geotechnical medium unlike terrigenous sand is an important building material in the exploitation of coral reef islands. Coral aggregate as an available aggregate resource for concrete has gained widespread recognition. Researchers have identified that the use of coral aggregate was feasible [3,6,16,17], even if the use of coral aggregate could decrease the mechanical properties compared to those of normal aggregate concrete because of the high porosity, water sorptivity, and low strength of coral aggregate. However, coral aggregate has internal curing properties similar to those of lightweight aggregate, which are important for the

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strength development of concrete, and the porous and rough-surface characteristics of coral aggregate also promote higher splitting tensile strengths compared to that of normal aggregate concrete [22].

However, the poor quality of coral aggregate and the harsh marine environment of coral reef islands can threaten the mechanical properties, durability, and long-term performance of coral aggregate concrete (CAC), which has attracted increasing attention from researchers. The addition of supplementary cementitious materials has inspired new methods to improve the strength and durability of concrete. Fly ash (FA) as a partial replacement of cement in concrete is commonly added for its pozzolanic activity and low cost. FA concrete shows an improved pore structure and denser matrix formation, which induce higher strength and better durability. However, the pozzolanic reaction of FA is slow and thus its contribution to the strength development occurs only at later ages. Therefore, the early strength of FA concrete is significantly reduced relative to non-FA concrete.

Cheng et al. [9] reported that the addition of FA decreased the compressive strength at both early and later ages, and also showed lower chloride resistance performance when FA was added. Chen et al. [8] found results similar to Cheng's findings. However, some researchers [34] reported that a decrease in the chloride ion diffusion coefficient occurs when FA is added to CAC.

In order to overcome the insufficient strength of FA at early ages, the incorporation of very small-size pozzolanic materials such as silica fume (SF) has been studied. Sun [26] reported that the incorporation of 20–30 wt% SF could increase the compressive strength, splitting tensile strength, and early strength. However, it is necessary to note that SF, while contributing significantly to concrete strength and chemical resistance, can increase the water demand and plastic shrinkage of concrete; these issues have attracted much research attention. Some researchers [23,5] have considered the combination of SF and FA in ternary cement systems. They observed increases in the compressive strength of FA concrete with the addition of SF at all ages. Thomas et al. [28] reported the superior durability performance of concrete containing both FA and SF. An improvement of early-age compressive strength and sorptivity of concrete with the incorporation of both FA and SF was reported by Barbhuiya et al. [4].

Although it has been identified that the incorporation of FA and SF has positive effects on the improvement of mechanical properties and durability of ordinary concrete, research on the effects of FA, SF, and ternary cementitious systems on the mechanical properties and durability of CAC remains insufficient and the topic requires further study. This study reports the effects of binary and ternary cementitious systems of FA and SF on the workability, compressive and splitting tensile strength development, and durability properties, including the water sorptivity and chloride permeability, of CAC. The micro-hardness of the interfacial transition zone (ITZ) in both CAC and normal aggregate concrete, as well as the effects of FA and SF on the micro-hardness change of CAC, are investigated. The poor service performance of CAC in harsh marine environments impedes its extension and application; therefore, this study is very important and significant in promoting the application and extension of CAC in infrastructural construction worldwide, and particularly for coral reef island countries.

2. Materials and experimental

2.1. Materials

Ordinary Portland cement PO42.5 (OPC), class F FA, and S98 SF were used in the tested mixtures. Their chemical compositions and physical properties are given in Table 1. Potable water was used as the mixing and curing water and a superplasticizer (SP) with the water reduction rate of 40% was employed in the study.

Coral sand and crushed coral reefs used as aggregates in the study were obtained from the South China Sea, as shown in Fig. 1. The morphological characteristics of the coral aggregate are observed by scanning electron microscope (SEM) in Fig. 2. As can be seen, the surface of the coral aggregate is rough, porous, and textured. Pores with diameters varying from 5 μm to 50 μm are found in both the surface and interior. The river sand used in this study had the same particle size distribution and fineness modulus of the coral sand. The particle size analyses of the coral sand and river sand used as fine aggregates with the maximum size of 4.75 mm are shown in Fig. 3. Crushed coral reefs and granite gravel with particle sizes of 5–20 mm were used as coarse

Table 1
Chemical compositions and physical properties of cementitious materials.

Test project	Specific gravity	mean grain size μm	Bulk density g/cm^3	specific surface area m^2/g	SiO_2 %	Al_2O_3 %	MgO%	Fe_2O_3%	CaO%	Na_2O%	SO_3%
SF	1.6–1.7	0.1–0.3	0.67	25	98	0.7	0.6	0.5	0.2	–	–
FA	2.1	7.1	0.78	0.33	58	30	2.8	4.3	1.5	3.2	–
OPC	3.1	–	–	0.35	23.55	5.64	1.67	2.85	64.17	0.26	0.49

(a) Coral reef (b) Crushed coral reef rubble (c) Coral sand

Fig. 1. Coral aggregate.

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