Research Article

Statistics and Analysis of the Relationship between Strength and Age of Coral Concrete

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In this study, based on the experimental results of this study and from the previous research, it is concluded that the compressive strength of coral concrete at 3, 7, 14, 21, 60, and 90 days reaches about 71%, 84%, 92%, 96%, 104%, and 110% of that at 28 days, respectively, indicating that the early strength development of coral concrete is significantly faster than that of ordinary concrete but slower in the later stage. A new model to characterize the strength-age relationship of coral concrete is proposed in this study, which is in good agreement with the experimental result, but for the long-term strength prediction of coral concrete in actual engineering, it is recommended to adjust the prediction results according to the environment and working conditions of coral concrete, and the adjustment coefficient could be approximately taken as 0.88. In addition, the effects of water-binder ratio (w/b), total dosage of cementitious materials (b), supplementary cementitious material (SCM) content, and aggregate properties, on the age strength development of coral concrete are studied.

1. Introduction

With the rapid development of human society, the development and utilization of marine resources have become an important issue for coastal countries and regions to expand their living space and increase resources, not just for national security. It is well known that the construction of islands and reefs is not only the support point of marine economic development but also the guarantee of national defense security. Therefore, the construction of island and reef is attracting increasing attention and becoming a new growth point of economic development, among which concrete is an important basic material for marine infrastructure construction and aggregate is an important part of concrete, accounting for more than 70% of the volume of concrete, which is in great demand in marine engineering construction. However, for most islands and reefs far away from the mainland, the construction cost is quite expensive due to the long transportation of traditional building materials and freshwater from the mainland to islands and reefs, and the construction period is difficult to guarantee due to the ocean transportation, which is often restricted by the complex marine climate. Hence, developing field construction materials for ocean engineering, such as broken reef-sand-sea water concrete and coral concrete, is becoming popular and attracting interest from the academic world. In areas such as the South China Sea, South Pacific, and Southeast Asia, which are rich in coral reef [1], on the premise of not damaging the marine environment, it may be an economic and feasible choice to use coral aggregate to prepare concrete in the construction of artificial islands.

Coral aggregate is a special kind of calcareous stone, with the characteristics of lightweight, high porosity, and strong water absorption, which makes it different from ordinary aggregate and light aggregate. In recent years, many researchers at home and abroad have carried out a series of experimental studies on the mechanical properties and structural application of coral concrete, which were summarized in detail by Wang et al. [2]. However, no consistent conclusion has been reached on the relationship between age
2 Materials and Methods

2.1 Materials Properties. The coral from the Southern China Sea island was all broken into irregular particles. After sieving, coral aggregate with a continuous particle size of 4.75 to 26.5 mm was used as coarse aggregate, as shown in Figure 1(a). Coral aggregate with continuous particle size less than 4.75 mm was used as fine aggregate, which had a fineness modulus of 1.7, as shown in Figure 1(b).

According to Chinese standard JGJ 52-2006 [3], the physical and mechanical properties of coral aggregate were measured, and the physical properties are listed in Table 1. The calculation formula of water absorption is

$$\rho_w = \frac{(G_1 - G_0)}{G_0} \times 100\%$$

where $\rho_w$ is the water absorption, expressed in percentage, $G_0$ is the weight of aggregate sample after drying, the unit is $g$, and $G_1$ is the weight of aggregate sample after it is saturated with water.

The OPC was made using 42.5 Ordinary Portland Cement, which was produced by China Tangshan Jidong Cement Co., Ltd. According to the method proposed by Han et al. [4], in order to improve the workability and the compactness of coral concrete and overcome the problem of long-term strength shrinkage of coral concrete, it is recommended to add slag and silica fume in the cementitious material. In this study, slag (SG) was produced by Hebei Silica fume (SF) was made by China Sichuan SLT Co., Ltd. Polycarboxylate superplasticizer (SP) was made by China Tianjin Metallurgical Special Materials Co., Ltd. with a solid content of 40%. With reference to literature [1], artificial seawater was prepared according to the composition of the seawater in the Southern China Sea. The chemical compositions of cementitious materials are listed in Table 2, and the chemical composition of seawater is given in Table 3.

2.2 Mix Proportion and Specimen Preparation. According to literature [4] and Chinese standard JGJ/T12-2019 [5], silica fume (SF) and slag (SG) were used to replace partial cement by weight, with the substitution rate $\delta_{sf}$ of silica fume ranging from 2.5%–7.5% and $\delta_{sg}$ of slag from 7.5%–22.5%, and the mass mixing ratio of silica fume (SF) to slag (SG) is 3:1, where $\delta_{sf} = m_f/b, b = m_{OPC} + \sum m_i, m_i$ is the dosage of supplementary cementitious materials, $b$ represents the total dosage of cementitious materials, and the mix proportions details are listed in Table 4, where $w_i$ denotes the apparent density of coral concrete.

It can be seen from Figure 1(b) that the water absorption $\rho_w$ of coral aggregate reaches more than 9% within 1–2 minutes, accounting for about 75% of saturated water absorption. Referring to literature [1], based on the working performance and strength of concrete, incomplete pretreating aggregate is adopted, and the configuration process was formulated as follows: (1) added the coarse and fine coral aggregate into the mixer and stirred for 1 minute; (2) added about 50% of the seawater, which could be absorbed by the aggregate and stirred for 1–2 minutes; (3) added the cementitious material and stirred for 1 minute; (4) added SP into the remaining seawater and mixed well, and then added the water into the mixture in 2–3 times and mixed continuously for 1–2 minutes. The slump and dispersion of coral concrete were measured immediately after mixing. After the concrete was placed in molds of a specific size, it was vibrated on a vibration table and then the exposed surface of concrete was covered with plastic film to prevent water dispersion. Afterwards, all specimens were demolded after curing under normal temperature $(20 \pm 3^\circ C)$ for 24 hours. Finally, all the specimens were placed in the standard curing room for curing until the test.

2.3 Testing Methods. The test methods of coral concrete were conducted according to Chinese standard GB/T 50081-2002 [6], the specimen size designed for cubic compression strength was $100 \times 100 \times 100 \text{mm}$ . The test ages of concrete were 3, 7, 14, and 28 days respectively. Three specimens were tested in each group, and the average value was obtained, as listed in Table 4. The tests were carried out using WAW-2000d electro-hydraulic servo universal testing machine, and the loading rate was selected as 0.5 MPa/s.

3 Test Results and Discussions

3.1 Relationship between Compression Strength and Curing Ages. In recent years, some scholars have carried out experimental studies on the relationship between compression strength and curing ages of coral concrete, with compression strength ranging from 15 to 55 MPa and curing age ranging from 3 to 28 days. A few scholars conducted compression strength tests of specimens with curing ages of 60 days and 90 days. The results have shown that the strength of coral concrete increases rapidly in the early stage, and some rules of strength growth were proposed. Equation (1) by Li [7] and equation (2) by Wang et al. [8] were suggested to describe the ratio of compression strength at specific curing days to that at 28 days, where $N$ represents the curing days:

$$\frac{f_{cu,N}}{f_{cu,28}} = \frac{N}{(N + 2)^4} \quad (1)$$

$$\frac{f_{cu,N}}{f_{cu,28}} = 0.1582 \ln N + 0.4702 \quad (2)$$

Due to the small amount of data and different test conditions, the relationship between relative compressive strength ($f_{cu,N}/f_{cu,28}$) and ages obtained by various researchers was not quite consistent. In order to verify the rationality of these conclusions, 14 groups of coral concrete at different ages were tested in this study. The relationship...
between $f_{cu,N}/f_{cu,28d}$ and age is shown in Figure 2. The results show that the average $f_{cu,N}/f_{cu,28d}$ at 3, 7, and 14 days are 22.9%, 9.0%, and 6% higher than those predicted by equation (1), respectively, and 14.5%, 9.0%, and 4.5% higher than those predicted by equation (2), respectively. The relative strength of coral concrete measured at 3, 7, and 14 days is
123.7%, 45.2%, and 17.1% higher than that calculated by equation (3) [7], respectively, which demonstrates that the early strength growth of coral concrete is significantly higher than that of ordinary concrete:

$$\frac{f_{cu,N}}{f_{cu,28}} = \log \frac{N}{\log 28}$$

In order to establish a representative equation to better describe the relationship between relative compressive strength and curing ages, the experimental data in this study and from previous research in other literature are collected and analyzed. Based on these data, the relationship between compression strength at specific curing ages and that at 28 days can be obtained, as shown in Figure 3. As can be

Table 3: Chemical composition of artificial seawater (mg/L).

|   | Cl  | Sulfate | Ca<sup>2+</sup> | Mg<sup>2+</sup> | HCO<sub>3</sub><sup>-</sup> | Na<sup>+</sup> | K<sup>+</sup> | Total salt content |
|---|-----|---------|----------------|----------------|----------------|------------|------------|------------------|
|   | 18399 | 2608 | 391 | 1323 | 155 | 9990 | 395 | 34260 |

Table 4: Coral concrete mix proportions.

| Groups | b  | OPC  | SG   | SF   | Total water | Coral | Coral sand | SP | Slump (mm) | 3d   | 7d   | 14d  | 28d  |
|-------|----|------|------|------|-------------|-------|------------|----|------------|------|------|------|------|
| C1    | 1  | 0.700 | 0.225 | 0.075 | 0.675       | 2.000 | 2.000      | 0.008 | 2040       | 155  | 24.6 | 27.3 | 34.0 | 36.4 |
| C2    | 1  | 0.700 | 0.225 | 0.075 | 0.585       | 1.721 | 1.721      | 0.009 | 2140       | 200  | 27.1 | 32.7 | 37.4 | 39.6 |
| C3    | 1  | 0.700 | 0.225 | 0.075 | 0.602       | 1.948 | 1.948      | 0.010 | 2020       | 205  | 25.4 | 31.6 | 34.2 | 36.8 |
| C4    | 1  | 0.700 | 0.225 | 0.075 | 0.503       | 1.320 | 1.320      | 0.011 | 2070       | 225  | 29.2 | 34.7 | 36.5 | 40.8 |
| C5    | 1  | 0.700 | 0.225 | 0.075 | 0.432       | 1.168 | 1.168      | 0.012 | 2110       | 255  | 35.7 | 36.3 | 42.5 | 46.3 |
| C6    | 1  | 0.700 | 0.225 | 0.075 | 0.432       | 1.284 | 1.051      | 0.012 | 2120       | 245  | 26.6 | 37.2 | 39.6 | 40.9 |
| C7    | 1  | 0.700 | 0.225 | 0.075 | 0.425       | 1.398 | 0.932      | 0.012 | 2120       | 240  | 34.8 | 35.2 | 39.1 | 44.3 |
| C8    | 1  | 0.700 | 0.225 | 0.075 | 0.392       | 1.038 | 1.038      | 0.016 | 2150       | 270  | 39.0 | 41.9 | 40.2 | 40.0 |
| C9    | 1  | 0.800 | 0.150 | 0.050 | 0.394       | 1.039 | 1.039      | 0.016 | 2220       | 240  | 35.1 | 43.5 | 44.7 | 49.7 |
| C10   | 1  | 0.900 | 0.075 | 0.025 | 0.406       | 1.036 | 1.036      | 0.016 | -          | 245  | 38.5 | 43.5 | 44.5 | 47.9 |
| C11   | 1  | 0.700 | 0.225 | 0.075 | 0.410       | 0.929 | 0.929      | 0.012 | 2170       | 240  | 34.1 | 45.0 | 46.3 | 50.9 |
| C12   | 1  | 0.700 | 0.225 | 0.075 | 0.375       | 0.927 | 0.927      | 0.023 | 2180       | 260  | 37.0 | 35.9 | 43.5 | 51.6 |
| C13   | 1  | 0.700 | 0.225 | 0.075 | 0.386       | 0.782 | 0.782      | 0.025 | -          | 270  | 38.7 | 43.0 | 49.9 | 52.4 |
| C14   | 1  | 0.700 | 0.225 | 0.075 | 0.356       | 0.782 | 0.782      | 0.030 | 2118       | 190  | 36.9 | 43.8 | 49.1 | 53.8 |

Figure 2: Relationship between (f<sub>cu,N</sub>)/(f<sub>cu,28</sub>) and age measured in this experiment. (a) Relationship between <em>f</em><sub>cu,N</sub>/<em>f</em><sub>cu,28</sub> and age. (b) Comparison of test results with predicted values.
Figure 3: Continued.
seen, there is an obvious linear relationship between \( f_{cu,28} \) and \( f_{cu,3}, f_{cu,7}, f_{cu,14}, \) and \( f_{cu,21} \) for coral concrete with various cubic compress strength respectively, as shown in Figures 3(a)–3(d), respectively. Thus, the relative compressive strength \( f_{cu,N}/f_{cu,28} \) at curing ages of 3, 7, 14, and 21 days can be described as equations (4)–(7), respectively, where \( n \) represents experimental data number and \( R^2 \) is the determination coefficient of regression analysis. As can be seen, only experimental data at curing age of 3 days have a relatively high dispersion with regression determination coefficient a bit smaller than 0.8 and results at curing ages of 7, 14, and 21 days all have good agreement. It may be due to that the early strength of coral concrete is more sensitive to some factors such as its composition and curing environment.

\[
\begin{align*}
N &= 3, \quad f_{cu,3}/f_{cu,28} = 0.6879 \left( R^2 = 0.7819 \right), \\
N &= 7, \quad f_{cu,7}/f_{cu,28} = 0.8459 \left( R^2 = 0.9283 \right), \\
N &= 14, \quad f_{cu,14}/f_{cu,28} = 0.0174 \left( R^2 = 0.9777 \right), \\
N &= 21, \quad f_{cu,21}/f_{cu,28} = 0.9606 \left( R^2 = 0.9969 \right), \\
N &= 60, \quad f_{cu,14}/f_{cu,28} = 1.0743 \left( R^2 = 0.9867 \right).
\end{align*}
\]

Equations (4)–(9) represent the relative compressive strength of coral concrete at age of 3, 7, 14, 21, 60, and 90 days, respectively. On this basis, the uniform relationship between relative compressive strength and age could be described as equation (10) by data regression.

\[
f_{cu,N}/f_{cu,28} = 0.1186 \ln(N) + 0.5912 \left( R^2 = 0.9774 \right).
\]

3.2. Effect of Composition of Coral Concrete on Compressive Strength Development. It can be seen from the above results that age is a very important factor affecting the strength development law of coral concrete, but it should not be the only one. Studies have proved that there are many factors affecting the development of concrete strength [9–20].

In recent years, based on the consideration of improving the mechanical properties of concrete and waste utilization, mineral admixtures such as slag, fly ash, and silica fume have become important supplementary cementitious materials (SCMs) of concrete [9–14]. It is found that the addition of SCM can effectively improve the physical and mechanical properties of concrete, such as workability, strength, and durability [15–20]. Previous investigations have found that the types and contents of SCM such as slag, fly ash, and silica fume have a certain impact on the strength of concrete and its growth with age [21–23]. In addition, the strength and its

![Figure 3: Relationship between compression strength at specific curing ages and that at 28 days. (a) 3 days. (b) 7 days. (c) 14 days. (d) 21 days. (e) 60 days. (f) 90 days.](image)
growth with an age of concrete could also be influenced by water-binder ratio (w/b) and aggregate properties [24, 25]. Based on the coral concrete test database in the references collected in this study, the effects of water-binder ratio (w/b), content of cementitious material (b), supplementary cementitious material (SCM) content (δ = m/b), and aggregate properties, on the strength and its development of coral concrete are studied.

3.2.1. Water-Binder Ratio. Previous studies have shown that the water-binder ratio (w/b) is one of the important factors affecting the compressive strength of concrete [23, 25]. As shown in Figure 4, with the increase of w/b, the curves of fcu,N versus w/b of coral concrete at different ages show a downward trend. In addition, it is reported that with the increase of w/b, the early strength growth of concrete slows down and the later strength growth accelerates [24, 26, 27], which is also verified in this study. With the increase of w/b, the curves of fcu,N/ fcu,28d versus w/b show a downward trend at 3 and 7 days (Figures 5(a), 5(c), and 5(d)), a moderate trend at 14 days (Figure 5(d)), and a slight upward trend at 60 and 90 days (Figures 4(a) and 4(b)).

3.2.2. Slag Content. As can be seen in Figure 6, with the increase of slag (SG) content (mSG/b), the early strength of coral concrete increases first and then decreases, that is, adding an appropriate amount of slag powder to replace partial cement has a positive impact on the strength of coral concrete, and the optimal replacement rate is about 15%, which is consistent with the conclusion reached in Reference [30]. In addition, it can be seen in Figure 7 that with the increase of mSG/b, fcu,N/ fcu,28d at 3, 7, 60, and 90 days increases first and then decreases, and fcu,N/ fcu,28d reaches the maximum when mSG/b is about 15%, but as mSG/b is lower than 15%, mSG/b has a mild effect on fcu,N/ fcu,28d at the early stage (3 and 7 days). Thus, as mSG/b reaches 30%, fcu,N/ fcu,28d at 3, 7, and 60 days was lower than that of the reference group (mSG/b = 0), as shown in Figure 8. This indicates that the proper addition of mineral powder has a significant positive effect on the later strength growth of coral concrete, which may be due to the higher volume of C-S-H gel and the lower content of free lime [31].

3.2.3. Fly Ash Content. Adding fly ash into concrete can reduce the cost and water demand of concrete, minimize the concrete shrinkage [30], and significantly reduce the diffusion rate of chloride ions in concrete, improving the durability of concrete structures in a chloride ion environment [31, 32]. However, it is also reported that the strength of concrete decreases with the increase of FA content [33, 34]. Figure 8 shows the effect of FA content (mFA/b) on the compressive strength of coral concrete at 3, 7, 28, and 90 days. The results show that with the increase of mFA/b, the strength of coral concrete decreases at 3, 7, and 28 days (Figures 8(a)–8(c) and Figures 9(b)), but increases at 90 days (Figures 8(d) and 9(b)). This is attributed to the lower pozzolanic activity than OPC in the early days, delaying the early hydration of cement and reducing the strength performance. With the increase of curing time, pozzolanic activity and concrete compactness increase, resulting in accelerated later strength of coral concrete. Thomas et al. [36] and Liu et al. [39] reported similar conclusions for ordinary concrete. In addition, it can be seen that with the increase of mFA/b, the curves of fcu,N/ fcu,28d versus mFA/b show a downward trend at 3 and 7 days and an upward trend at 90 days, as shown in Figures 9(a), indicating that FA inhibited the early strength development and accelerated the later strength growth.

3.2.4. Silica Fume Content. According to previous studies, it has been reported that the addition of silica fume can improve the compressive strength of concrete, which may be due to that it not only makes the voids in C-S-H gel filled, but also forms nanostructured C-S-H gel material, thereby improving the microstructure of concrete [39]. It can be seen from Figure 10 that the addition of silica fume can significantly improve the strength of coral concrete and its strength shows a positive growth trend with the increase of silica fume content (mSF/b). However, the influence of mSF/b on fcu,N/ fcu,28d of coral concrete is related to the w/b. For high w/b (e.g., w/b = 0.555 in Reference [38], as shown in Figure 11(a)), with the increase of mSF/b, fcu,N/ fcu,28d increases first and then decreases and fcu,N/ fcu,28d reaches the maximum with mSF/b of 2%, and as mSF/b > 4%, the early strength growth (e.g., fcu,3d/ fcu,28d and fcu,7d/ fcu,28d) would be even lower than that of the reference group (mSF/b = 0). However, it has a moderate impact on the later relative strength (e.g., fcu,90d/ fcu,28d). For low w/b (e.g., w/b = 0.3 in Reference [39], as shown in Figure 11(b)), the addition of silica fume can obviously increase the compressive strength of coral concrete, but mSF/b has a slight effect on fcu,N/ fcu,28d (Figures 10 and 11(b)).

3.2.5. Total Dosage of Cementitious Materials. Wang [40] found that compared with ordinary concrete, coral concrete has a higher water-binder ratio and cementitious material consumption. Li [7] reported that among the influence of various raw materials on the strength of seawater coral concrete, the dosage of cementitious material has the greatest effect. It can be seen from Figure 12 that as the total dosage of cementitious material b ≤ 1000 kg/m³, with the increase of b, the compressive strength of coral concrete at 3, 7, 14, 28, and 90 days shows an increasing trend; however, as b exceeds 1000 kg/m³, the strength decreased significantly. In addition, fcu,N/ fcu,28d at 3 and 7 days increased with the increase of b, but that at 14 and 90 days changes moderately, as shown in Figures 13(a) and 13(b), indicating that as b ≤ 1000 kg/m³, increasing the total dosage of cementitious material has a significant positive impact on the strength of coral concrete but has a moderate impact on its relative strength.
Figure 4: Continued.
Figure 4: Effect of w/b on $f_{cu,N}$. (a) At 3 days. (b) At 7 days. (c) At 14 days. (d) At 21 days. (e) At 28 days. (f) At 60 days. (g) At 90 days.

Figure 5: Continued.
Figure 5: Effect of w/b on \(\frac{f_{cu,N}}{f_{cu,28d}}\). (a) \(\frac{f_{cu,N}}{f_{cu,28d}}\) versus w/b \([28]\), (b) \(\frac{f_{cu,N}}{f_{cu,28d}}\) versus w/b \([29]\), (c) \(\frac{f_{cu,N}}{f_{cu,28d}}\) versus w/b \([26]\), and (d) \(\frac{f_{cu,N}}{f_{cu,28d}}\) versus w/b in this text.

Figure 6: Continued.
3.2.6. Properties of Coral Aggregate. Wang et al. [2], Li [7], and Da [24] reported that the characteristics of coral aggregate, such as porosity, strength, stiffness, and particle shape, have an impact on the strength of coral concrete, and coral concrete has higher pore size and porosity and lower compressive strength and density than ordinary concrete under the same mix proportion, which is due to coral aggregate’s high porosity of 40–60%, as shown in Figure 14. Many investigations [7, 8, 24–26, 29, 38–53] have shown that the barrel compressive strength of coral aggregate is about 2 to 6.5 MPa and lower than that of ordinary aggregate, which is one of the primary sources for the low strength and high brittleness of coral concrete. Yodsudjai et al. [54] found that for low strength aggregate, the concrete strength will increase with the increase of aggregate strength, and coral aggregate conforms to this law. From literature [24], it is found that there are some differences in the physical and mechanical properties of coral aggregate due to different origins or weathering degrees. Under the same conditions, the average compressive strength of coral concrete with aggregate barrel compressive strength of 5.2 MPa is about 10% higher than that with 3.8 MPa, while the average compressive strength of coral concrete prepared with unweathered coral aggregate is 12% higher than that with weathered aggregate [24]. As shown in Figures 14(c) and 14(d), due to the low strength of coral aggregate, some coral aggregate particles on the failure surface were crushed or penetrated by cracks. This means that the coral concrete prepared by specific coral aggregate has a corresponding upper limit strength, once the strength of coral concrete approaches or exceeds the upper limit value, it would be difficult to increase more. This explains why it is difficult to prepare a high-strength coral concrete with low-strength coral aggregate.
Figure 8: Effect of (m)FA/(b) on (f)cu,N. (a) At 3 days. (b) At 7 days. (c) At 28 days. (d) At 90 days.

Figure 9: Effect of (m)FA/(b) on (f)cu,N/(f)cu,28d. (a) fcu,N/fcu,28d versus mFA/b [13] and (b) fcu,N versus mFA/b [13].
Figure 10: Effect of \( m_{SF/b} \) on \( f_{cu,3d} \). (a) At 3 days. (b) At 7 days. (c) At 28 days. (d) At 90 days.

Figure 11: Effect of \( m_{SF/b} \) on \( f_{cu,N} \). (a) \( f_{cu,N}/f_{cu,28d} \) versus \( m_{SF/b} \) [27] and (b) \( f_{cu,N}/f_{cu,28d} \) versus \( m_{SF/b} \) [13].
In addition, it can be observed that there is no obvious crack at the interface between coral particles and binder paste, as shown in Figure 14(b). This is mainly due to the internal curing of porous coral aggregate, which absorbs water in the early hydration stage and releases water in the later stage, resulting in the increase of the volume of hydration products and the densification of interfacial transition zone (ITZ) [55, 56]. Under the same test conditions,
the bond strength between the coral aggregate and binder paste and the microhardness value (HV) of coral concrete in the ITZ are significantly higher than that of ordinary concrete [7, 57].

3.3. Model Validation. In order to verify the practicability and reliability of the proposed model (equation (10)), the relative compressive strength of coral concrete at different ages is predicted by equations (1)–(3) and equation (10), respectively. The predicted results \( \frac{f_{cu,N}}{f_{cu,28}} \) by equation (10), \( a_2 \) by equation (1), \( a_3 \) by equation (2), and \( a_4 \) by equation (3) and the measured results \( a_0 \) are all listed in Table 5, and the corresponding curves and measured data are plotted in Figure 14.

The results have shown that the \( a_2 \) (by equation (1)) was significantly lower than the measured results, which is attributed to the fact that equation (1) does not consider the rule that coral concrete strength increases with age, so that the relative deviation between the predicted result and the measured one also increases with age. The \( a_3 \) calculated by equation (2) is slightly lower than the corresponding \( a_0 \) at the early stage, but significantly higher than \( a_0 \) in the later stage. However, the \( a_4 \) calculated by equation (3) is significantly lower than the corresponding \( a_0 \) at the early stage, and far higher than \( a_0 \) in the later stage, so that it reaches 210% of \( a_0 \). By contrast, the predicted results \( a_1 \) by equation (10) are closest to the measured results. Similar to ordinary concrete, the strength of coral concrete also increases with age, but the development law is significantly different. As can be seen from Table 5, the \( a_1 \) at 3, 7, 14, and 21 days is about 118.5%, 40.8%, 14.1%, and 4.2% higher than \( a_0 \), respectively but 12.4% and 16.7% lower at 60 and 90 days, respectively, as shown in Figure 14(a). This confirms that coral concrete has faster early strength growth and slower later strength growth, which is different from that of ordinary concrete mixed and cured with freshwater.

It can be observed that for the coral concrete prepared in the laboratory (3–90 days), the relative deviation \( E_1 \) of equation (10) is very small, within 3.5%. However, for the coral concrete used in practical engineering, the results “Data 1” measured by Chen et al. [58] with ages of 1.5 y, 16 y, and 19 y, and “Data 2” measured by Rick [59] with ages of 33 y and 38 y are all significantly lower than the \( a_1 \) of equation (10), as shown in Table 5 and Figure 14(b). There may be three main reasons for this. Firstly, chloride composition has a significant effect on the early strength growth of coral concrete but has a moderate effect on the later strength [56], and the strength calculation model is proposed based on short-term test results; secondly, the environment (high temperature, salt spray, radiation, humidity, etc.) of marine engineering project is significantly different from that of the laboratory [59]; thirdly, coral concrete applied in practical engineering bears the long-term load, which is significantly different from that of the laboratory specimens [59]; finally, the low strength of coral aggregate restricts the greater growth space of coral concrete strength.

In general, the proposed model (equation (10)) can be directly used to predict the short-term strength relationship of coral concrete (e.g., \( t \leq 90 \) days). For the long-term strength prediction of coral concrete in practical engineering, it is suggested to modify the prediction results. Zhao [58] reported that adverse effects of chemical components such as \( \text{Cl}^- \), \( \text{SO}_4^{2-} \), and \( \text{CO}_2 \) existing in the marine environment on the strength of plain coral concrete could be negligible. Rick [59] pointed out that coral aggregate and seawater are not the primary sources of rapid reinforced concrete deterioration, and factors, such as the degree of atmospheric exposure, splashing by seawater, concrete cover to reinforcing steel and surface cracks, are more important,
Figure 14: Images of coral concrete. (a) SEM image of coral aggregate. (b) Interface transition zone between aggregate and binder. (c) Failure mode of specimens. (d) Failure section.

Table 5: Verification of age strength prediction model for coral concrete.

| Time  | 3d  | 7d  | 14d | 21d | 28d | 60d | 90d | 1.5y | 16y  | 19y  | 33y  | 38y  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(a_0\) | 0.712 | 0.836 | 0.916 | 0.961 | 1.000 | 1.042 | 1.097 | 1.170\(\text{e}^{-2}\) | 1.232\(\text{e}^{-2}\) | 1.241\(\text{e}^{-2}\) | 1.527\(\text{e}^{-2}\) | 1.570\(\text{e}^{-2}\) |
| \(E_1(\%)\) | -1.7 | -1.3 | -0.9 | -1.4 | 3.4 | 2.6 | 14.4 | 31.5 | 32.2 | 11.7 | 9.7 |
| \(a_1\) | 0.721 | 0.822 | 0.904 | 0.952 | 0.986 | 1.077 | 1.125 | 1.178\(\text{e}^{-2}\) | 1.425\(\text{e}^{-2}\) | 1.443\(\text{e}^{-2}\) | 1.501\(\text{e}^{-2}\) | 1.516\(\text{e}^{-2}\) |
| \(E_2(\%)\) | -15.7 | -6.9 | -4.5 | -5.0 | -6.7 | -7.1 | -10.8 | -14.9 | -18.8 | -19.4 | -34.5 | -36.3 |
| \(a_3\) | 0.644 | 0.778 | 0.888 | 0.952 | 0.997 | 1.118 | 1.182 | 1.468 | 1.842 | 1.869 | 1.957 | 1.979 |
| \(E_3(\%)\) | -9.6 | -6.9 | -3.1 | -0.9 | -0.3 | 7.3 | 7.7 | 25.5 | 49.5 | 50.6 | 28.2 | 26.1 |
| \(a_4\) | 0.330 | 0.584 | 0.792 | 0.914 | 1.000 | 1.229 | 1.350 | 1.892 | 2.603 | 2.654 | 2.820 | 2.862 |
| \(E_4(\%)\) | -53.7 | -30.1 | -13.5 | -4.9 | 0.0 | 17.9 | 23.1 | 61.7 | 111.3 | 113.9 | 84.7 | 82.3 |

Note: \(a_0\) is the average relative compressive strength measured in this study and in the collected literature; \(a_1, a_2, a_3, a_4\) are the relative compressive strength predicted by equation (10) and equations (1)–(3), respectively; \(E_i\) is the relative deviation of \(a_i\) (predicted results) relative to \(a_0\), \(E_i = (a_i - a_0)/a_0\); "#" denotes the measured average results of coral concrete in the actual project by Chen et al. [58]; "∗" denotes the measured average results of coral concrete in the actual project by Rick [59]; "∗∗" denotes that the calculation result has been multiplied by 0.88 for adjustment.
indicating that coral concrete cracking and reinforcement corrosion are the key sources to the ultimate irreversible decay of concrete strength. Therefore, it is recommended to multiply the result calculated by equation (10) by an adjustment coefficient, which could be taken according to the actual environment and working conditions of coral concrete buildings, such as the degree of atmospheric exposure, seawater splashing, salt fog infiltration, concrete

\[
\frac{f_{cu,N}}{f_{cu,28}} = 0.1186 \ln (N) + 0.5912 \\
\frac{f_{cu,N}}{f_{cu,28}} = 0.1582 \ln (N) + 0.4702 \\
\frac{f_{cu,N}}{f_{cu,28}} = \frac{N}{1 + N} \\
\frac{f_{cu,N}}{f_{cu,28}} = \log \frac{N}{\log 28}
\]
cracking, and reinforcement corrosion. In the absence of test data, the adjustment coefficient could be approximately 0.88, as shown in equation (11). The “fcu,N” values predicted by equation (10) corresponding to different ages are in good agreement with the measured results, where the prediction results corresponding to “Data 1” and “Data 2” are multiplied by the adjustment coefficient of 0.88, as shown in Figures 15, 16 and 17. “Test data” represents the average relative compressive strength measured in this study and in the collected literature and “Engineering data 1” and “Engineering data 2” represent the measured average results by Chen et al. [58] and Rick [59], respectively.

\[
\frac{f_{cu,N}}{f_{cu,28}} = 0.88(0.1186 \ln (N) + 0.5912).
\]

4. Conclusions

The relationship between strength and age of coral concrete is studied experimentally. Based on the experimental results obtained in this study and collected from existing literature, the following conclusions can be drawn:

1. The early strength development of coral concrete is significantly faster than that of ordinary concrete, and the compressive strength at 3 days, 7 days, 14 days, 21 days, 60 days, and 90 days reaches about 71%, 84%, 92%, 96%, 104%, and 110% of that at 28 days, respectively.

2. Similar to ordinary concrete, the strength of coral concrete also increases with age, while its development law is obviously different, and the strength of coral concrete increases faster in the early stage (0–28 d) and slower in the later stage.

3. Based on the experimental results, the strength-age relationship of coral concrete is obtained, and a new model to describe the relationship is proposed. And the results predicted by the proposed model are in good agreement with the experimental results.

4. Compressive strength of coral concrete is affected by many factors. It is found that the early strength increases with the increase of b, mSF and decreases with the increase of w/b, mFA; the later strength increases with the increase of mFA, b and decreases with the increase of w/b. The early relative strength increases with the increase of b and decreases with the increase of w/b, mFA, while the later relative strength increases with the increase of w/b, mFA, and characteristics of coral aggregate have an impact on the strength of coral concrete.

5. For the long-term strength prediction of coral concrete in actual engineering, it is recommended to adjust the results predicted by the proposed model according to the environment and working conditions of coral concrete building, and the adjustment coefficient could be approximately 0.88. Due to the few existing coral concrete application cases and limited comparable data, the model would be further verified.

6. The model (equations (10) and (11)) proposed in this study is mainly suitable for predicting the age strength of seawater coral concrete and could be used as a reference for the preliminary prediction of age strength of seawater ordinary concrete or seawater lightweight aggregate concrete.

Data Availability

The data used to support the findings of this study are included within the article.
Ethical Approval

The authors state that the research was conducted according to ethical standards.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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